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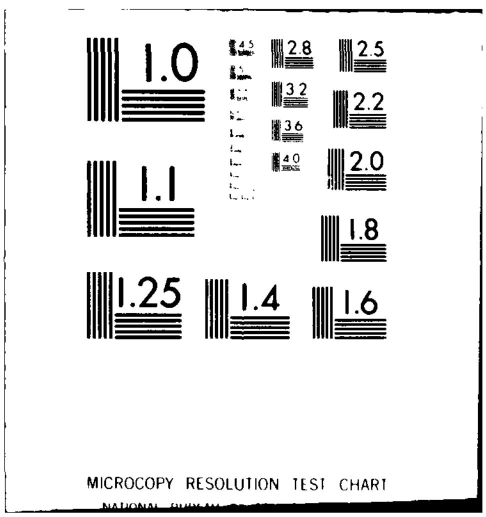
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# RATIONAL DESIGN OF TUNNEL SUPPORTS: AN INTERACTIVE GRAPHICS BASED ANALYSIS OF THE SUPPORT REQUIREMENTS OF EXCAVATIONS IN JOINTED ROCK MASSES

by

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The Distinct Element methods portray a rock mass as a two-dimensional assembly of discrete blocks. There are no restrictions of block shapes or magnitudes of displacements and rotations. In the configurations used in this report, the Distinct Element method is coupled to a graphics terminal so that movements of the blocks are visually available as the computer calculates them.

In Chapter II, a brief survey of the methods commonly used to analyze the behavior of jointed media is presented. Common to these methods surveyed is

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the realization that the observed behavior of a jointed mass is different from the behavior of a continuum.

Chapter III is devoted to providing numerical verification of the Distinct Element method. In particular, several comparisons to limit equilibrium solutions are presented. The comparisons are favorable

The other chapters are concerned with the behavior of a jointed rock mass when disturbed by an excavation. The discussion covers two broad topics: (a) excavations that are stable without external support, and (b) excavations that require external support. The behavior of the jointed mass is typically illustrated by means of contact force distributions within the mass and through the development of arching. For those excavations requiring support, computer-generated ground reaction curves are presented.

## PREFACE

This is the final report of a study performed by the University of Minnesota, Minneapolis, Minnesota, under Contract No. DACW45-74-C-0066 with the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi. This work was sponsored by the Office, Chief of Engineers, U. S. Army. This study, which was originally funded under the Civil Works Investigation Study (CWIS) Program, "Materials-Structures," by the Missouri River Division, Corps of Engineers, resulted in a report entitled "Rational Design of Tunnel Supports: A Computer Model for Rock Mass Behavior Using Interactive Graphics for the Input and Output of Geometrical Data." Following this preliminary study with its emphasis on rock mass behavior, the WES continued the contract under the CWIS Program, "Materials-Rock."

The study was conducted by Dr. M. D. Voegele, Department of Civil and Mineral Engineering, University of Minnesota, under the supervision of Professor Charles Fairhurst, Department Chairman. Technical contract monitor for the WES was Mr. J. B. Palmerton, Research Civil Engineer, Engineering Geology and Rock Mechanics Division (EG&RMD), WES. Dr. D. C. Banks, Chief, EG&RMD, was the Contracting Officer's Representative.

During the period of this contract and preparation of the report, the Directors of the WES were COL J. L. Cannon, CE, and COL N. P. Conover, CE. Technical Director was Mr. F. R. Brown.

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# CHAPTER I

# INTRODUCTION

The goal of engineering analysis is intelligent design. This is true for disciplines which are based upon theoretical concepts discovered literally centuries ago as well as for more recently recognized disciplines such as Rock Mechanics engineering. Whereas the researcher in most fields of engineering has at his disposal analytical techniques which have been proven through decades of use and sound analytical development, the Rock Mechanics researcher has a limited number of analytical techniques at his disposal. Many of the problems encountered in the field of Engineering Geology and Mining engineering require the specification of the response behavior characteristics of a jointed rock mass. Foundation design requires a knowledge of the stiffness of the rock mass so that settlements and forces can be predicted accurately. Highway cuts in rock must be designed so as to be completely safe from slope failures. Mines, shafts and tunnels must all be designed with a knowledge of the behavior of the rock mass. The economic design of open pit mines relies heavily on the pit slope angle; a change of only a few degrees in the slope angle has a significant effect on the stripping ratio and thus the economic success of the mining venture. The design of dam foundations or abutments is particularly sensitive to the behavior of the rock mass. Settlements which can be tolerated by dam foundations are quite small. The failure to consider all of the response characteristics of a rock mass in such situations has in the past led to catastropic failures and the attendant loss of life. In all of these problems the role of mass jointing can play a significant role

in the mass response, but all too frequently the exact behavior of the joints is poorly understood. Intelligent design requires an understanding of this behavior.

The analytic techniques at the disposal of the Rock Mechanics engineer upon which the design must be based are quite limited, and typically have been borrowed from other fields. The principles of classical mechanics are often used as an aid in analysis but it is frequently observed that the behavior of a rock mass cannot be characterized by the assumptions inherent in these classical methods. The fundamental assumptions of a continuum characterization, homogeneity and linearly elastic response, are often seen to be too limited in scope to characterize adequately the behavior of a rock mass. That group of materials which we classify as rock is typically non-homogeneous, anisotropic, and often discontinuous; of these characteristics the discontinuous nature of the rock mass is certainly the most influential in governing the ultimate behavior of the mass when subjected to some external stimulus. Constitutive relations can be generalized to include the effects of anisotropic structure; for example, a recent paper by Singh (1973) describes the development of an anisotropic continuum model in which the average influence of planar features can be taken into account.

Finite Element methods provide an accurate, approximate, method of solving problems in elasticity. The formulation of a "joint" element by Goodman et al. (1968) greatly increased the potential of the Finite Element methods in Rock Mechanics problems. However, Finite Element methods still strictly model a continuum and thus

large displacements are not possible except through iteration with each new iteration utilizing parameters derived from the previous iteration.

To portray adequately the response of a jointed rock mass requires the correct modeling of the discontinuities present, that is, the joints must have both normal and shear stiffness, they must obey some type of failure law and, most important, the blocks defined by the joints must be free to undergo large displacements and rotations if conditions so dictate. A computer model which satisfies all of these criteria was presented by Cundall (1971b).

The computer model for simulating progressive large scale movements in blocky rock systems which has since become known as the Distinct Element method utilizes semi-rigid rock blocks to characterize the behavior of a discontinuous rock mass. The interaction between the blocks is governed by realistic friction laws and simple stiffness parameters. There are no arbitrary limits on the amount of displacement and rotation allowed to each block and any block is permitted to touch any other block. True progressive failure is thus modeled and the mode of failure is automatically selected by the program since the system fails by that mode with the lowest stability. The program allows individual study of the effects of joint geometry, joint parameters, loading conditions and excavation procedure.

The Distinct Element method portrays a rock mass as a two dimensional assemblage of discrete blocks. There are no restrictions on block shapes or magnitudes of displacements and rotations. In the configuration used in this dissertation, the program is interfaced

with a graphics terminal so that movements of the blocks can be observed as the computer calculates them.

The equation governing the behavior of the blocks is solved in an explicit rather than implicit manner. Because the jointed rock mass may fail in such a way that the movement of the blocks leads to a new equilibrium position, an adequate block model must take this into consideration. An implicit solution assumes path independence; that is, the final answer must be the same no matter how the blocks move to get there. It seems safe to assume that path dependent phenomena such as separation along joints, stick-slip behavior of joint surfaces and block interlocking could not be modeled adequately except by an iterative procedure using very small time increments. It should be recognized that by using this approach, one would simply be using an implicit solution to model the solution that would have been obtained directly by an explicit approach.

The major approximation inherent in the Distinct Element method is that deformations occur along the surfaces of the rock blocks. This is accomplished by modeling each block as being rigid with what amounts to a thin elastic region around the perimeter. A consequence of this is that the program should produce the best solutions in situations where deformation is governed by movement along joint surfaces. On the other hand, those situations where elastic deformations of the rock mass are of the same order of magnitude as the movement along the joint surfaces are perhaps best modeled by elastic solutions of the Finite Element type or by a continuum characterization.

Joint inclination and confining pressure play a significant role in the determination of the failure mode. The combination of the conditions of low confining pressures and favorable (or unfavorable dependent on viewpoint) joint orientation can lead to failure modes that are joint controlled. When viewed in terms of overall mass stiffness (i.e., deformation resulting from the application of external load), it can be seen intuitively that those failures in situations of low overall stiffness are probably joint controlled while the higher stiffness models exhibit failures that are essentially independent of jointing.

The research described in this dissertation has as its basis two main goals. First, owing to the relative newness of the Distinct Element method, a verification study has been undertaken to determine whether or not the Distinct Element method calculates solutions similar to other methods commonly used to analyze jointed rock masses. The second goal of the research is to apply the Distinct Element method to an engineering problem; in this particular case to the design of supports and the behavior of the rock mass surrounding an underground excavation. Underlying these two main research goals are several attendant yet equally important goals. One underlying theme concerns the application of computer interactive graphics to engineering analysis. Another underlying theme concerns the potential perspective of the Distinct Element method.

To introduce the investigations of the behavior of jointed rock masses performed with the Distinct Element method, a brief survey of the methods commonly used to analyze the behavior of jointed media is

presented. Common to those methods surveyed is the realization that the observed behavior of a jointed mass is different than the behavior of a continuum. Several of the methods adopt the approach that the behavior of the jointed mass is fundamentally similar to that of a continuum; the same basic equations are assumed to govern both models but the constitutive relations are modified for the jointed models to simulate the presence of jointing. Other methods typically propound the fact that the jointing governs the mass behavior and thus postulate governing equations based upon assumed or observed behavior. This introductory section concludes with a brief overview of the Distinct Element formulation and presents several examples illustrating applications of the Distinct Element program.

Confidence in the use of approximate numerical techniques such as the Distinct Element method can best be developed by comparing calculated results to known solutions. However, for the particular case of the behavior of a jointed rock mass, comprehensive analytical solutions do not exist. The second major portion of this dissertation summarizes the results of numerous analyses, the sole purpose of which was to demonstrate the validity of solutions calculated by the Distinct Element method. The models chosen for comparison are typically simple and care was exercised to ensure that the behavior of the chosen model was described adequately by its solution. Most of the models chosen for the comparisons were based upon Limit Equilibrium principles, and the Distinct Element calculated solutions were seen to agree quite well with the Limit Equilibrium solutions in all cases. This general theme of comparison to existing solutions is not limited to this portion of the dissertation,

however. Wherever possible in the later portions of the dissertation, every attempt is made to compare Distinct Element calculated solutions to other solutions.

The remainder of the dissertation is concerned with the behavior of a jointed mass when disturbed by an excavation. The discussion covers two broad topics: excavations which are stable without external support; and, excavations which depend upon externally applied support for stability. The interactive capabilities of the graphics terminal are fully utilized in these studies, both to observe the behavior of the mass and to modify the model while the program is running.

Chapter 4 presents the results of analysis of stable excavations in jointed rock. The behavior is illustrated by means of contact force distributions within the mass and interpreted as being governed by the development of arches within the mass. The mechanisms responsible for the development of the arching behavior are investigated and an interpretation utilizing arching theories is presented.

Chapter 5 presents the results of analyses of excavations in jointed rock which are not stable unless an external support is provided. The behavior is described quantitatively by ground reaction curves, relating the deflection of the excavation roof to the magnitude of the required support force. These curves reflect the interaction between the rock mass and the support system in an attempt to guide the research along paths of investigation that are consistent with current thought regarding rational modeling of tunnel behavior. The results of these analyses are then compared to several methods, primarily of an observational nature, commonly used to design support

systems for excavations in jointed rock. The rationale governing these comparisons is an attempt to provide some manner of analytic support for these routinely used design schemes.

The dissertation concludes with a summary of pertinent results and a critical assessment of the potential of the method in engineering analyses and design. The assessment of the potential emphasizes the limitation of the model in its present configuration with particular reference to the mini-computer based configuration. Suggestions for further development of the model are also presented, outlining areas of potentially fruitful research.

# CHAPTER II

# THE ANALYSIS OF THE BEHAVIOR OF A ROCK MASS CONTAINING PLANES OF DISCONTINUITY

## 2.1 Introduction

Before introducing the concepts underlying the Distinct Element model, a brief, historical review of the methods of analysis commonly used when dealing with the behavior of a discontinuous rock mass is presented. An exhaustive bibliography on jointed rock has been avoided, since a significant portion of all publications dealing with Rock Mechanics would need to be included. Rather, this chapter presents an overview of the methods of analysis used when dealing with jointed rock, concentrating on those methods that are accepted by engineers involved in actual design. The overview is relatively complete, including examples of all methods recognized to be in use at the present time.

A general survey of the response characteristics of a jointed rock mass is presented first, to enumerate those behavior mechanisms which must be incorporated in any analysis of a jointed rock mass if it is to portray accurately the behavior of the mass.

An overview of the methods of analysis is then presented. The methods lend themselves nicely to categorization in the following groups:

1) Direct application of the principles of Soil Mechanics to the behavior of rock masses;
2) application of elastic theory, both in the classical

sense and by use of Finite Elements;

3) behavior models including direct physical modeling as well as models based on observed behavior; and,

4) methods of analysis utilizing Limit Equilibrium theories as developed in the fields of plasticity and soil mechanics.

The chapter concludes with a brief introduction to the Distinct Element method of calculating the behavior of a mass separated into distinct blocks by jointing or other discontinuity surfaces. The applicability of the model is discussed by way of a short presentation of worked examples. It is hoped that the examples selected give some insight into the scope and power of the method as well as demonstrating typical problems which can be analyzed by the method.

## 2.2 The Response Characteristics of a Rock Mass

The obvious trend in the past several decades has been to excavations, both in mining ventures and the construction of civil works projects, on a scale never before attempted. The mining of vein type deposits frequently takes place in poor quality rock; in the case of the civil works projects, the best sites in terms of rock quality have already been selected for previous construction. Since it was no longer possible to ignore the rock behavior, the traditional concept of the soundness and stability of a rock mass had to be re-evaluated. In recognition of this requirement, a study group, the International Study Group for Geomechanics, was founded in Salzburg, Austria in 1951. The goal of this study group was to develop relations among all workers dealing with construction in rock and to develop a practical approach to the mechanics of rock masses.

The findings of the study group, which was succeeded by the International Society of Rock Mechanics in 1962, were presented by John (1962), and the following few paragraphs, quoted directly from John's paper, attempt to summarize the philosophy of the Salzburg group.

> "Because the particular properties of rock as foundation and construction material deviate, in many respects, from those of other foundation materials, rock mechanics is compelled to follow its own course. The continuity of soil masses ... resulted in methods for analyzing a continuum, thus defining the concept of soil mechanics. In situ rock, however, contrary to the wide spread assumption in foundation engineering, is rarely homogeneous; rarely without mechanical discontinuities. Therefore, rock mechanics is, in most cases, to be a study of a jointed structure, of a discontinuum."

The philosophy of the Salzburg group emphasizes the collaboration between civil and mineral engineers and geologists. The interrelation of engineers and geologists is readily apparent in the fundamental concepts of Rock Mechanics as outlined by John:

1) "For most engineering problems, the technical properties of a rock mass depend far more on the system of geological separations within the mass than on the strength of the rock material itself. Therefore, rock mechanics is to be a mechanics of a discontinuum, that is, a jointed medium"

2) "The strength of a rock mass is considered to be a residual strength that, together with its anisotropy, is governed by the interlocking bond of the unit rock blocks representing the rock mass"

3) "The deformability of a rock mass and its anisotropy result predominately from the internal displacements of the unit blocks within the structure of a rock mass."

C. Jaeger (1964) presented a similar philosophy to that of John and noted that engineering calculations should take a far more detailed view of the actual state of the rock mass. Recognizing the inadequacy of the (then) present state of the art, he outlined a program of suggested research, emphasizing model tests and investigations of stress distributions in jointed media.

Fairhurst (1967), in assessing the influence of defects and discontinuities on the behavior of a rock mass noted that failure in a rock mass always begins at some structural defect and that the analysis of the behavior of the mass must consider: the orientation and distribution as well as the magnitude of the applied forces; the distribution and orientation of structural defects with respect to the applied forces; and the energy available to cause continuing movement in the mass.

One final requirement of any method used to calculate the response of a jointed mass is that it should incorporate all of the kinematically possible failure modes. In addition to sliding on discontinuity planes, rotation of individual blocks about their centroids is also kinematically possible as reported in field exposures by Muller (1964) and DeFreitas and Watters (1973) and on a laboratory scale by Hoffman (1970). An analysis incorporating only force equilibrium and ignoring moment equilibrium could easily result in the neglect of an important response of the mass.

## 2.3 Direct Application of Soil Mechanics Theories

Recognizing that large displacements preclude the use of elastic theory, Seldenrath (1951) idealized the strata comprising European coal measures as masses of loose structure, and attempted to apply Soil Mechanics principles to the problems of calculating fracture planes due to subsidence and calculating loads on props at a working longwall face. To the extent that he assumed reasonable values for friction coefficients, he was able to generate results that were confirmed in practice.

Morrison and Coates (1955) presented a method for the estimation of stresses surrounding a circular vertical shaft by means of plastic flow relationships deduced from Mohr's circle of stress. They questioned the utility of their method for practical design and concluded that although the approach was better than a simple elastic analysis, the actual material behavior was still more complex.

Wilson (1959) applied general Soil Mechanics principles to the problem of slope stability in open pit mines. He concluded that failures of cut slopes in fractured and fissured rock were often the result of uplift pressures in the water behind the slope face. Observing that the strength of granular material appeared to be independent of particle size provided that a constant degree of compactness was maintained, Wilson extrapolated this result to the analysis of the behavior of broken and fissured rock. Since the scale of the jointing relative to the size of the pit was small, Wilson analyzed the stability of cut slopes using the principles

of Soil Mechanics.

Jaeger (1970) analyzed highly jointed and broken rock by regarding the jointing as random and applying the laws of Soil Mechanics to its behavior. His analysis suggested that values of Youngs' modulus measured by plate bearing tests on jointed material for which the plate covered several joints were in reasonable agreement with laboratory values measured on actual specimens of the material containing many joints.

## 2.4 Elastic Theories Applied to Rock Masses

Elastic analyses of discontinuous or jointed masses can be conveniently grouped into two classes although the difference between the methods is one of application rather than fundamental difference in the theory. The first class comprises methods of analysis which directly utilize classical elastic theory; frequently the input parameters are modified to reflect different behavior modes due to the presence of discontinuities. The second class comprises Finite Element type analyses wherein the continuum is discretized and a stiffness relationship is formulated for applied forces and nodal point displacements. This latter class is obviously well suited to the situation of varying material properties throughout the mass.

### 2.4.1 Classical continuum elastic theories

Obert, Duvall, and Merrill (1960) restricted their analysis of the design of underground openings to competent rock but included horizontally stratified rock provided that the bond between layers was weak.

Beam and Plate theory were used for the analysis but it was noted that requirements of an elastically perfect, homogeneous, isotropic mass precluded the possibility of any fracturing in the roof unless it was parallel to the span direction.

Barla (1970) presented constitutive relations for the non-linear and time dependent behavior of rock masses but did not present relations for discontinuous masses.

Smart (1970) developed a continuum model consisting of rigid cubical blocks set in a clay matrix and found good agreement with field data.

Singh (1973a, 1973b) used strain energy principles to derive general constitutive equations for a rock mass containing an arbitrarily oriented set of orthogonal, discontinuous joints in terms of a "stress concentration factor" matrix (which he computed by Finite Element analysis). His model gave good results for regions of low stress gradient but was found to give poorer results in regions of high stress gradient.

### 2.4.2 Finite Element analyses

One particular type of elastic analysis has gained acceptance since its inception. The Finite Element analysis, particularly in light of the modifications described below, has become a routinely used tool in Rock Mechanics problems.

Zienkiewicz et al. (1968) noted that linear elastic solutions indicating regions of tension in a rock mass were probably unrealistic for the general case of a cracked and fissured mass. Using a Finite Element formulation with an included "stress transfer" iteration they were able to calculate a solution with no tension present in the mass. They also demonstrated that the solution provided a lower bound to the load at failure.

Goodman, Taylor, and Brekke (1968) succeeded in incorporating a zero thickness element with normal and shear stiffnesses within the Finite Element formulation. With this special "joint element" they modeled failure in tension and shear, rotation, arch develop-

ment and collapse patterns in jointed rock.

Hoffman (1970) compared the results of model tests with the results of Finite Element analyses and found that the large deformations and geometric changes in the jointed mass were not compatible with the assumptions inherent in the Finite Element method.

St. John (1972) analyzed the behavior of rock slopes in open pit mines using Finite Element models incorporating joint behavior. He concluded that the technique provided acceptable results provided small displacement theory was relevant but stressed the need for field data to verify the constitutive laws used in the program.

Chappell (1974 a; 1974 b), and Burman, Trollope, and Philp (1975) related the behavior of a jointed medium to rigid body displacements of block centroids. The modified Finite Element formulation replaced the elastic blocks with rigid ones and connected the block centroids with "joint" elements capable of modeling the combined block and joint responses of stress versus strain and moment versus rotation. Appropriate moduli were obtained by physical experiments.

Wang and Sun (1970 a, b) and Wang, Sun, and Ropchan (1972) used Finite Element analyses to determine stresses in gravity loaded open pit slopes. These stresses were then incorporated in a Limit Equilibrium analysis to determine the safety factor of the slope with respect to sliding on a preselected failure plane.

Manfredini, Martinetti, and Ribacchi (1975) used Finite Element analyses of slopes to demonstrate the inadequacy of Limit Equilibrium methods in design. One interesting, though not unexpected, conclusion from their study was that the intact properties of the rock mass played very little part in the behavior of the jointed medium.

## 2.5 Jointed Mass Behavior Models

The jointed mass behavior models have been arbitrarily separated into three groups. The first comprises true physical models including both those models where similitude requirements are met and those whose purpose is simply to demonstrate the kinematics of failure. The second group, photoelastic modeling, is a sub group of the first group but owing to the special type of information it yields, is considered separately. The third group comprises theories of behavior which are primarily based upon either empirical data and the results of model tests or postulated behavior mechanisms.

### 2.5.1 Physical models

Lang (1964) used physical models for assistance in understanding the behavior of underground power stations. The most significant result of this research was aid in visualizing deformation behavior of jointed media.

Krsmanovic and Milic (1964) undertook a comprehensive series of tests to determine pressure distribution in a discontinuum subjected to external loads. Their results demonstrated that the pressure distribution was most sensitive to the original state of stress of the mass.

Trollope (1966) examined the behavior of a trapezoidal opening in a jointed rock mass. His work indicated two zones above the opening: a triangular "suspended zone" above the opening and a stable region outside of the "suspended zone".

Goldstein et al. (1966) investigated the behavior of models of jointed slopes by using a centrifuge. The goal of their research was to investigate the different failure conditions of slopes cut in jointed rock.

Fumagalli (1968) outlined the general principles of mechanical similitude including the incorporation of discontinuity surfaces for the proper physical scale modeling of problems in rock.

Edwards (1968) constructed a model of an open pit slope with wooden blocks as an aid to the interpretation of deformation measurements obtained in the field. An important conclusion of his work was that even though the models were not truly scaled they reproduced the measured phenomena better than an elastic analysis.

Gaziev and Erlikman (1971) embedded strain gauges in plaster blocks and built models to examine pressure distributions in discontinuous masses. They concluded that the state of stress is characterized by two "streams" of stresses following the directions of the principal joint sets.

Erguvanli and Goodman (1972) stressed the importance of kinematic models to observe possible failure modes, as well as scale models which could more accurately predict true behavior patterns.

Goodman (1972) outlined the use of the base friction model to observe the kinematic behavior of rock masses containing discontinuities.

Barton (1974) examined the deformation of discontinuous models consisting of approximately 40,000 blocks. Cut slopes were

excavated in the model after consolidation. The outcome of the experiments was compared to Finite Element analyses and photoelastic studies reported in the literature at that time. In all cases the "reasonable" behavior as predicted by theory failed to materialize.

### 2.5.2 Photoelastic models

Lang (1961) used photoelastic models to study the effects of the presence of joints in the roof of an underground opening. He also presented some guidelines for rock bolting based upon patterns of stress transfer observed in bolted photoelastic models.

Maury (1970) examined the distribution of stresses in horizontally stratified masses by means of photoelastic models. He noted that the observed behavior was fundamentally different from that predicted by continuum theory.

Brcic and Nesovic (1970) analyzed detailed two dimensional models of dam foundations by photoelastic models. Their results suggested that the presence of discontinuities was a most significant parameter in the definition of the foundation bearing capacity.

Ergun (1970) performed a photoelastic analysis of a biaxially loaded plate with orthogonal joints and noted that the stress distribution was affected by: voids in the joints, the ratio of applied pressure, the joint inclination, and the stress history.

Chappell (1973) investigated the interactions of underground openings in jointed media photoelastically. His conclusion was that the mechanisms of slip, rotation, and interlock controlled

the load distribution. Furthermore, he noted that the interaction between a number of openings tended to accentuate these mechanisms.

### 2.5.3 Observational models

The observation of the behavior of discontinuous masses as well as the behavior of laboratory models has led to several theories of behavior which for lack of a better name are herein termed observational models. These observational models attempt to predict behavior in light of stress disruption/or redistribution across planes of discontinuity such as joints, or, in the case of soils, grain contact. They often utilize the information gained from model experiments or collected from real situations and extract response patterns which are postulated to hold for a large class of problems.

Terzaghi (1946) carried out tests in railroad tunnels in the eastern Alps by inserting wooden blocks of known strength properties in timber sets. On the basis of the results of these tests, he postulated the expected loads on tunnel supports as a function of the degree of jointing of the rock mass under consideration.

Trollope (1957, 1961) developed an arching theory of force distribution within granular masses by a statical equilibrium analysis of a mass consisting of systematically packed, smooth, rigid spheres. He applied this theory to block jointed models to deduce general design principles. The same approach was used by Trollope and Brown (1965) to develop general equations for the

distribution of pressure in a discontinuous mass beneath a strip loaded foundation.

Hyashi (1966) formulated an approach to determine the distribution of stresses in a fissured foundation in terms of the combined Pascal distribution. The effects of cohesion and frictional resistance were incorporated by means of an iterative application of Bousinesq's equation. His model recognizes a transient depth below which slip no longer occurs along joint planes. In the absence of cohesion or frictional resistance his model reduces to that postulated by Froelich (1933) who idealized the contact stresses in stacked cylinders as an assemblage of tiered, simple beams.

Lane (1961) and Lutton (1970) presented empirical charts relating slope height to inclination. Their data indicated trends, but they recognized that adverse geologic structure could invalidate the use of the charts.

Abel (1966) constructed a statistical model for the estimation of support loads in a tunnel from measured steel set loads, geologic and construction factors. He noted that although the principles of analysis were general, every tunnel must be considered as a separate problem.

Ross-Brown (1973) collected data concerning the stability of cut slopes in open pit mines throughout North America. He concluded that stability problems were too complex to be summarized by statistical relationships and that each mine needed to be considered as a separate entity in light of the experience obtained

in other mines.

More recently, Wickham, Tiedemann, and Skinner (1972), Bieniawski (1973), and Barton, Lien, and Lunde (1974) have presented empirically derived rock mass classification schemes for predicting loads on tunnel supports. The classification schemes result from the statistical manipulation of data collected during construction in rock and consider parameters such as joint spacing, orientation, infilling, and the presence of water.

## 2.6 Limit Equilibrium Analyses

The basic principles of Limit Equilibrium applied to jointed rock masses are basically not different from the principles of the analysis of soil slopes as advocated by Fellenius (1936) or Bishop (1955). Owing to the degree of indeterminacy in the problem, assumptions must be made regarding the magnitude of some forces as well as their point of application.

A large portion of the literature on the stability of rock slopes comprises work on the analysis of the sliding behavior of tetrahedral wedges of rock by means of stereographic projection (e.g. John, 1968). Although two dimensional problems can be handled by this method, the amount of work required in the calculation as opposed to a simple graphical solution hardly merits the effort. Limit Equilibrium of three dimensional wedges is not considered in this review.

John (1962) presented a graphical analysis of the stability of a wedge of rock defined by joint planes and a cut surface. To determine the magnitude of rock anchor forces, he utilized conditions of limiting equilibrium by assuming that full frictional resistance would be developed along the plane of sliding - effectively allowing him to specify the force polygon.

Bray (1966, 1967 a, b) substituted the equations for principle stress in the Mohr-Coulomb-Navier relation to develop the ratio of principle stresses at failure by sliding in a jointed mass as a function of the orientation of the principle stresses and the friction coefficient. An interesting outcome of this analysis

comes by superposing a system of multiple fractures; in this model the value of the stress ratio approaches that of the active pressure coefficient as used in soil mechanics.

Jennings (1970) noted that failure in rock slopes did not necessarily follow a single plane. Rather, the failure surface that developed was often stepped. Utilizing Limit principles, the equations he presented incorporated sliding on a discontinuity as well as failure through intact rock.

Calder (1970) used Limit principles to analyze the stability of slopes in jointed rock. His analysis demonstrated that contrary to the case of slope failure in soils, significant changes in cut slope angle in jointed masses often have no effect on the degree of stability.

Hoek (1970) presented design charts, based on Limit Equilibrium principles, for the rapid assessment of the stability of slopes excavated in jointed rock. The assumptions necessary to produce the charts are conceded to be severe but are common to all analyses of this type.

Rosengren (1971) presented the results of a comprehensive analysis of the stability of blocks and wedges formed by the joint systems. Whereas the factor of safety as used by most investigators relates total driving force to total resisting force, Rosengren's definition of factor of safety contains one term relating available friction to required friction and another term relating required cohesion to available cohesion.

Pentz (1971) investigated the situation where the failure criterion was not linear; a simple power law was used to relate normal stress to shear stress in place of the commonly used Mohr-Coulomb-Navier relationship.

Gaziev and Rechitski (1974) used Limit Equilibrium principles to analyze a rock slope with multiple slip modes possible. Their analysis located the layer with the minimum stability factor. The overall stability of the mass was then related to the individual layer stabilities.

Statistically based modifications of Limit Equilibrium methods have also been presented by several authors.

McMahon (1971) introduced design procedures that determine the probability that a rock slope will be undercut by joints that lie in unstable orientations. On the basis of these assumptions, and utilizing Limit Equilibrium principles, he arrived at curves relating probability of failure to slope angle.

Serrano and Castillo (1974) introduced probability density functions for the strength of discontinuities and the matrix as well as for block size and combined them with Limit Equilibrium principles to generate a stability curve for a rock slope in terms of probability of failure.

## 2.7 An Evaluation of the Techniques Commonly used in Jointed Mass Modeling

The preceding literature survey dealt with the numerous methods commonly used to predict the behavior of rock masses containing planes of weakness. It is of interest to present a brief summary of this survey that emphasizes what, in particular, advantages each of the methods offer.

The observational type methods are typically the first "analytical" method associated with engineering analyses. It is to the credit of men like Terzaghi that they recognized that the degree of jointing present in a rock mass could be the most significant factor to be considered in a design. However, most investigators pursuing this method noted that although the method usually worked quite well for a given problem, the information gained was generally not of use at other sites. Most recent investigators have tried to overcome this shortcoming by statistical manipulation of a large amount of data.

Elastic solutions, and in particular, modified elastic solutions are recognized as having shortcomings, but are usually conceded to be fairly accurate in those cases where the jointing is homogeneous throughout the rock mass. The modified solutions usually attempt to account for the jointing by anisotropic mass behavior. It is interesting to note that one of the leading proponents of this method of solution "... has now abandoned his earlier view ... that an 'equivalent orthotropic medium' can be constructed to fairly represent the deformability of regularly

jointed rock ..." (Goodman, 1974). Goodman makes this statement on the basis of dilatancy and stress dependent behavior of the joints and suggests that the more influential discontinuities should be treated as individual rock mass components.

The application of soil mechanics theories to the analysis of the behavior of jointed rock masses has been successful in those cases where the scale of the jointing relative to the problem was sufficiently small. However, if detailed analysis, on the scale of the jointing, is required, the method lacks validity.

The use of Limit Equilibrium principles holds much promise if it is possible to reduce the intricacies of the problem to the point where a "handleable" number of equilibrium equations can be written, and if the joint behavior may be represented as simply as is done in Limit Equilibrium methods. The main problem with this type of approach is that the necessary assumptions often tend to oversimplify the problem - if too many assumptions need to be made to reduce the indeterminacy, then the model may no longer be representative of the problem to be solved.

Physical modeling seems to offer the best solution to modeling the behavior of jointed rock masses, since the behavior is exactly modeled if similitude requirements are met. However, it is virtually impossible to set up the identical physical models which are necessary for parametric variation, and the cost of a detailed model can be prohibitive.

The Distinct Element method offers a combination of the capabilities required to predict the behavior of jointed rock

masses. The joints are modeled as the most significant components of the problem. There is no need to oversimplify the problem and the data structures can be stored permitting a given geometry to be analyzed as many times as desired.

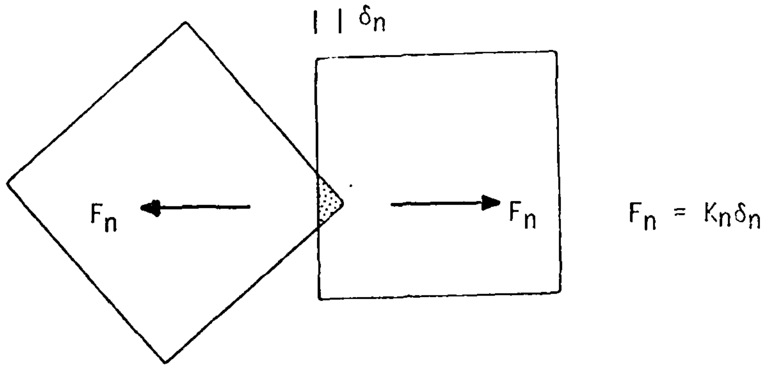
It is in the context of a reproducible "physical" model that the Distinct Element method is used in this dissertation.

## 2.8 The Distinct Element Method

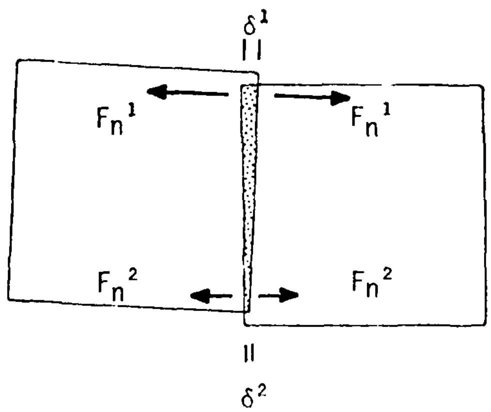
The Distinct Element method introduced by Cundall (1971 a, b) is a computer based analysis that simulates the behavior of a system of discrete, semi-rigid rock blocks. Block interactions are governed by realistic friction and stiffness laws. Each block may undergo unlimited displacement and rotation while progressive failure is modeled. In its present formulation the program is run in an interactive mode on a dedicated mini-computer coupled to a cathode ray tube (CRT) graphic output device. The CRT is used both for the input of geometric and material information as well as for the output data which consists of drawing the movements of the blocks as a function of time. The description presented follows Cundall (1971 b).

The program calculation cycle comprises force-displacement relations for the block contacts and laws of motion for the block centroids. Very simple relationships are used to relate normal force to normal displacement and shear force to shear displacement.

The normal force-displacement relationship owes its simplicity to the assumption that the normal stiffness of a joint plays a very small role in the failure process of the rock mass and that shear force does not affect normal force. Thus normal force is assumed proportional to the overlap between two blocks. Diagramatically,

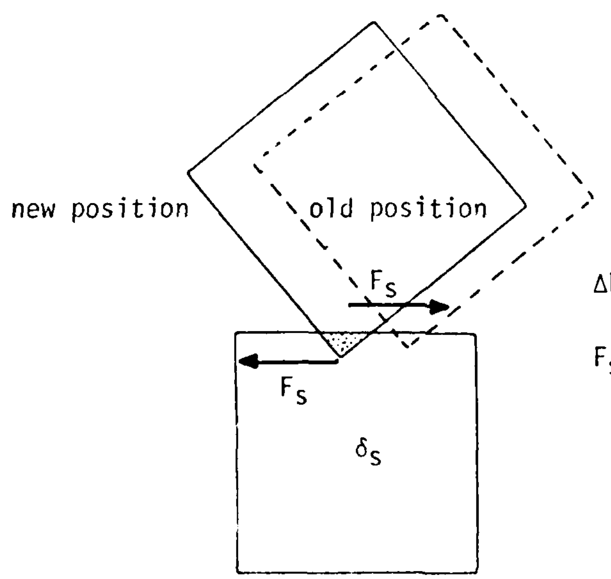



where constant of proportionality $K_n$ is the joint normal stiffness and the resultant force acts upon both blocks. In the more likely case where two faces together form a joint, equilibrium is maintained by two point contacts, thus:




Cundall argues for the validity of representing a joint by two point contacts by noting that owing to irregularities present on a real joint, contact will occur only at discrete points, quite possibly only two.

The shear force-displacement relationship cannot be described by such a simple formulation because the shear force depends upon the past history of movement of the blocks as well as the amount of normal force. To account for this, the shear force must be calculated incrementally with the incremental amount of shearing force assumed proportional to the relative movement of a block corner along another block face. The incremental shear force is then added, noting the sense of movement, to the shear force already existing between the two blocks. Diagramatically:




$$\Delta F_s = K_s \delta_s$$

$$F_s = F_s^{old} + \Delta F_s$$

where the proportionality constant $K_s$ is the joint shear stiffness.

Although not strictly necessary from a physical standpoint, the normal force is also calculated incrementally in the program

so that all forces are derived from incremental displacements. This formulation does, however, simplify the task of incorporating nonlinear phenomena, such as dilatation, associated with the normal stress.

Two failure laws are incorporated in the program. Since it is probably unrealistic to have tensional resistance across a joint, a "no tension" criterion is adopted at each time step, by simply setting normal forces that become negative to zero. The criterion governing shear failure is the Mohr-Coulomb-Navier law. At every time step, the shear force at each contact point is tested and limited to a maximum force, which is dependent upon the normal force.

The force-displacement relations are thus used to calculate the set of forces acting on each block solely due to the geometric position of each block relative to its neighbors. The forces acting on each block may be resolved into an equivalent force vector and a moment acting on the block centroid. If a law of motion is now implemented (in this case Newtons second law) the linear acceleration vector can be calculated as the quotient of the resultant force and the mass of the block. Similarly, the rotational acceleration is the quotient of the resultant moment and the rotational moment of inertia of the block. By choosing a suitable time step, these accelerations may be numerically integrated twice to give the displacement of the block. For example, in the x direction:

$$v_x^{new} = v_x^{old} + \frac{F_x}{m} \cdot \Delta t$$

$$u_x^{new} = u_x^{old} + v_x^{new} \cdot \Delta t$$

v = velocity

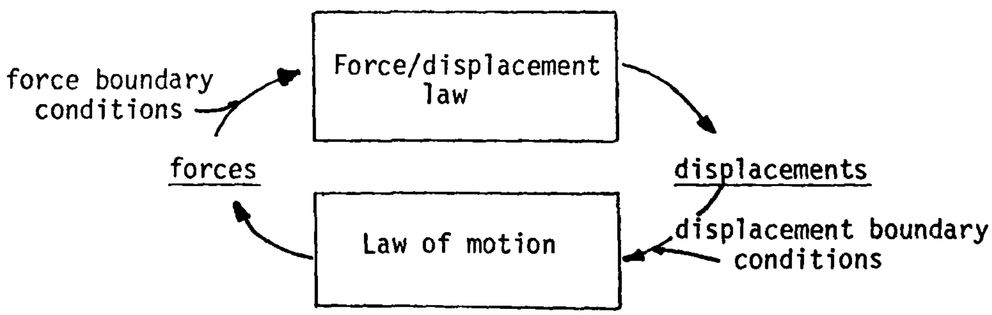
u = displacement

m = mass

$F_x$ = Force on block in x dir

with similar equations for the y direction and rotation. The time step cannot be made arbitrarily large, or rapid geometric changes would not be modeled accurately. However, a more subtle reason for the limit on the time step is that owing to numerical instabilities in the solution of the equations, there is a limit to the maximum time step. This is discussed in more detail by Cundall (1971 a) along with the damping requirements of the equations.

The complete calculation cycle can be summarized as:




In addition to the main calculation cycle, routines are needed to keep track of the coordinates of contacts; the use of arbitrarily large displacements and the attendant large number of possible contact points requires the implementation of a dynamic memory

allocation scheme. This scheme is discussed in Appendix B along with a more complete listing of the equations comprising the main calculation cycle. A complete discussion of the fundamental algorithm of the program is given by Cundall (1974).

## 2.9 Applications of the Distinct Element Method

As a conclusion to this chapter, several examples illustrating the application of the Distinct Element method to problems involving the response behavior of jointed rock masses are presented. The problems range in complexity from modeling a rock slope as a single block bounded by a joint plane and a tension crack at the crest, to examining the behavior, as failure progresses, of a jointed mass being mined by caving techniques. The examples chosen illustrate most of the salient features and capabilities of the Distinct Element method; however, the potential of the method extends much farther. Particular examples of extended applications could include true blasting analysis, coupled fluid flow behavior and incorporation of elastic stresses and strains.

The problem of the correctness of the solutions obtained by the Distinct Element method will be addressed in the next chapter; for the present time the correctness of the solutions should be accepted. Alternatively, the examples can be viewed in light of kinematics only with calculated displacement modes and forces interpreted in light of experience and intuition.

### Example 1 - Stabilization of a Failing Rock Slope

The rock slope illustrated in Figure 2.1(a) consists of a single block bounded by a joint plane dipping approximately $25^\circ$ out of the face of the slope and a vertical tension crack at the crest of the slope. The friction coefficient of the joint plane is .15,

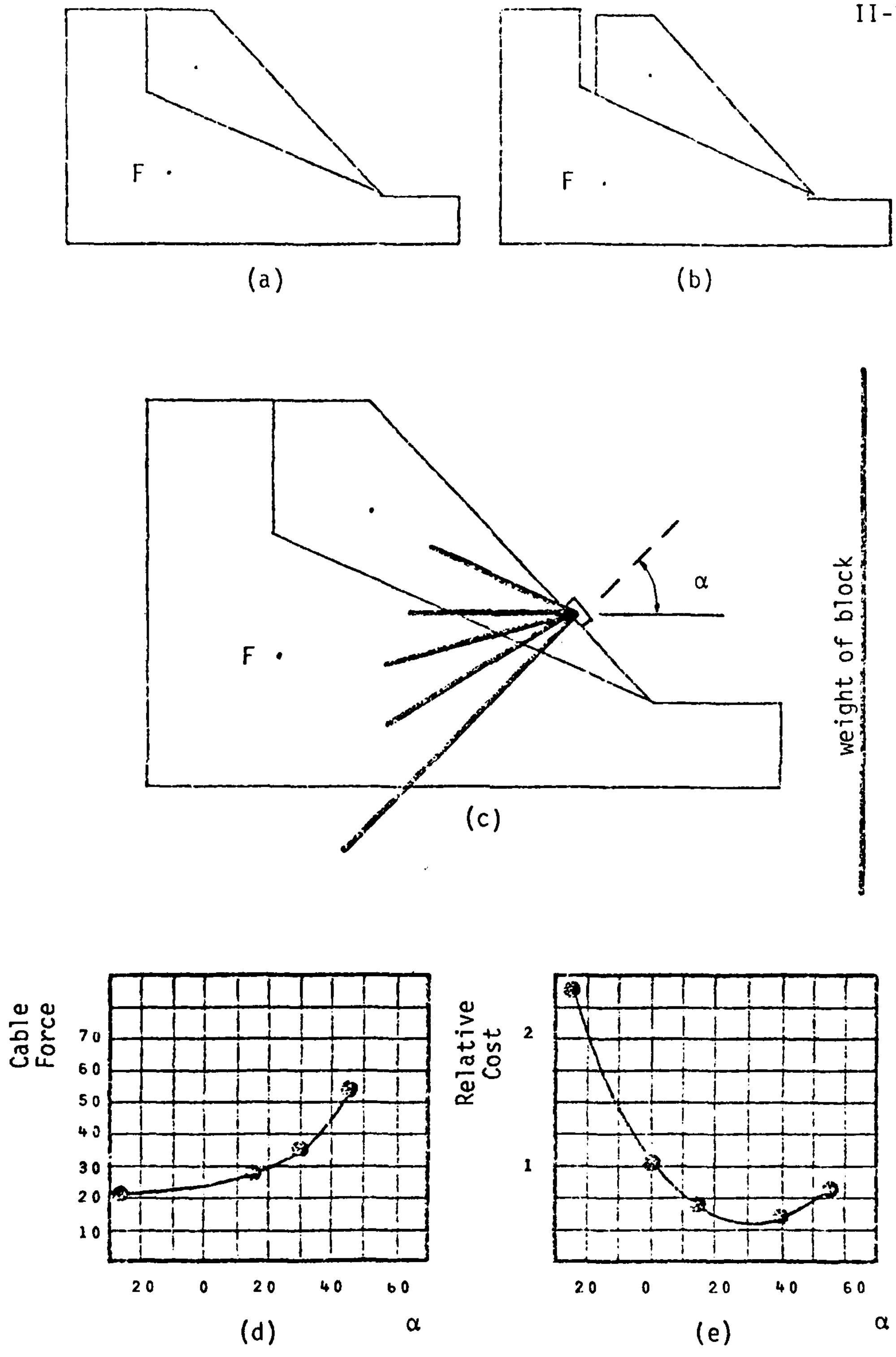



Figure 2.1 Stabilization of a Failing Rock Slope

corresponding to an angle of $8.5^{\circ}$; thus the block should be unstable and is seen to move on the screen as illustrated in Figure 2.1(b). Note that the block centroids are identified by a dot and that an "F" at a centroid means that the block is fixed in space, that is, not free to move.

To investigate the affect of inclination of an applied stabilizing force, a small block is placed on the slope and forces are applied at various angles. As can be seen in Figures 2.1(c) and (d), the smallest force required to stabilize the slope corresponds to an angle of inclination equal to the dip of the joint. Also, the required stabilization force increases as the bolt inclination becomes perpendicular to the joint plane. However, the length of bolt or cable required for stabilization is a minimum when this length is normal to the joint. By assuming a simple relationship governing bolting costs, it is possible to determine the optimum inclination for installation of stabilizing forces. A simple, yet reasonable estimate of relative cost is obtained by assuming that cost increases linearly with length and force relative to some base cost (in this case the horizontal bolt was chosen), this can be expressed as:

$$\text{Cost}_i = \text{Cost}_H \left(\frac{l_i}{l_H} \cdot \frac{F_i}{F_H}\right)$$

Assigning an arbitrary figure of 1 to the cost of the horizontal bolt, Figure 2.1(e) which relates the bolt cost to inclination, can be plotted. From this figure it can be seen that based upon the

assumed cost relationship, the optimum angle of inclination of the stabilizing force is approximately 30°.

Realistic cost data can be used to refine the cost relationship and much more complicated slope geometries can be modeled with the Distinct Element method.

Example 2 - Horizontally Stratified Mine Roof

Figure 2.2 illustrates a horizontally stratified mine roof; there are no joints exposed within the span of the roof. The only information that can be obtained by using the Distinct Element method in a problem such as this is the weight distribution on the pillars which in this case could readily have been obtained by inspection. The Distinct Element method in its present formulation does not incorporate elastic behavior of the elements; all deformations occur on joint surfaces. For problems where elastic deformations are important an elastic analysis such as Finite Element analysis should be used. For this particular problem however, beam theory could have been used to determine the bending moments and deflections (see, for example, Obert, Duvall, and Merrill 1960).

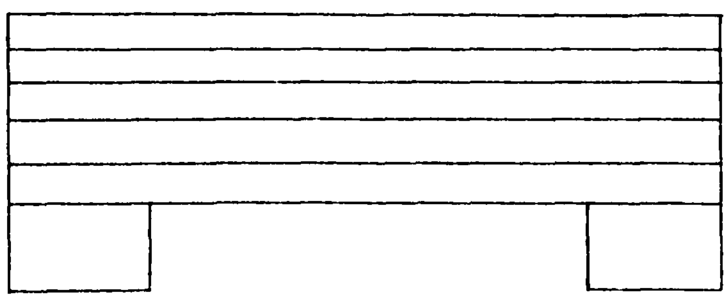


Figure 2.2 A Horizontally Stratified Rock Mass

Example 3 - A Gravity Retaining Wall

Illustrated in Figure 2.3(a) is a retaining structure which is required to prevent movement of the jointed mass to its left. Three friction coefficients are involved in a problem such as this: $\phi$, the friction angle of the joints within the mass; $\phi_b$, the friction angle for sliding on the base of the wall; and, $\phi_w$, the friction angle for sliding of the rock mass along the wall. By selectively varying these parameters it is possible to illustrate several aspects of the behavior of the wall in response to loading. Figure 2.3(b) illustrates the behavior of the wall when $\phi = 26^\circ$ and $\phi_b = \phi_w = 45^\circ$; as the blocks begin to move outward, the wall cannot slide along its base and thus begins to rotate as evidenced by the single contact vector at the lower right hand corner of the wall. The lower left hand corner of the retaining wall is actually lifted off the plane of sliding. The situation is, however, stable.

In Figure 2.3(c) another stable situation is illustrated. In this case, $\phi = \phi_b = 19^\circ$ while $\phi_w = 45^\circ$. The "9" printed on a surface indicates that that surface is assigned the friction behavior specified for material type 9. This analysis indicated that as the rock mass moved outward the base of the retaining wall moved until sufficient frictional resistance to maintain stability was generated along the base. Some rotation of the retaining wall has occurred and is indicated by the differing lengths of the contact vectors along the base of the retaining wall.

As a final variation of this example, illustrated in Figure 2.3(d), an analysis with $\phi_w = \phi_b = \phi = 19^\circ$ is presented. This

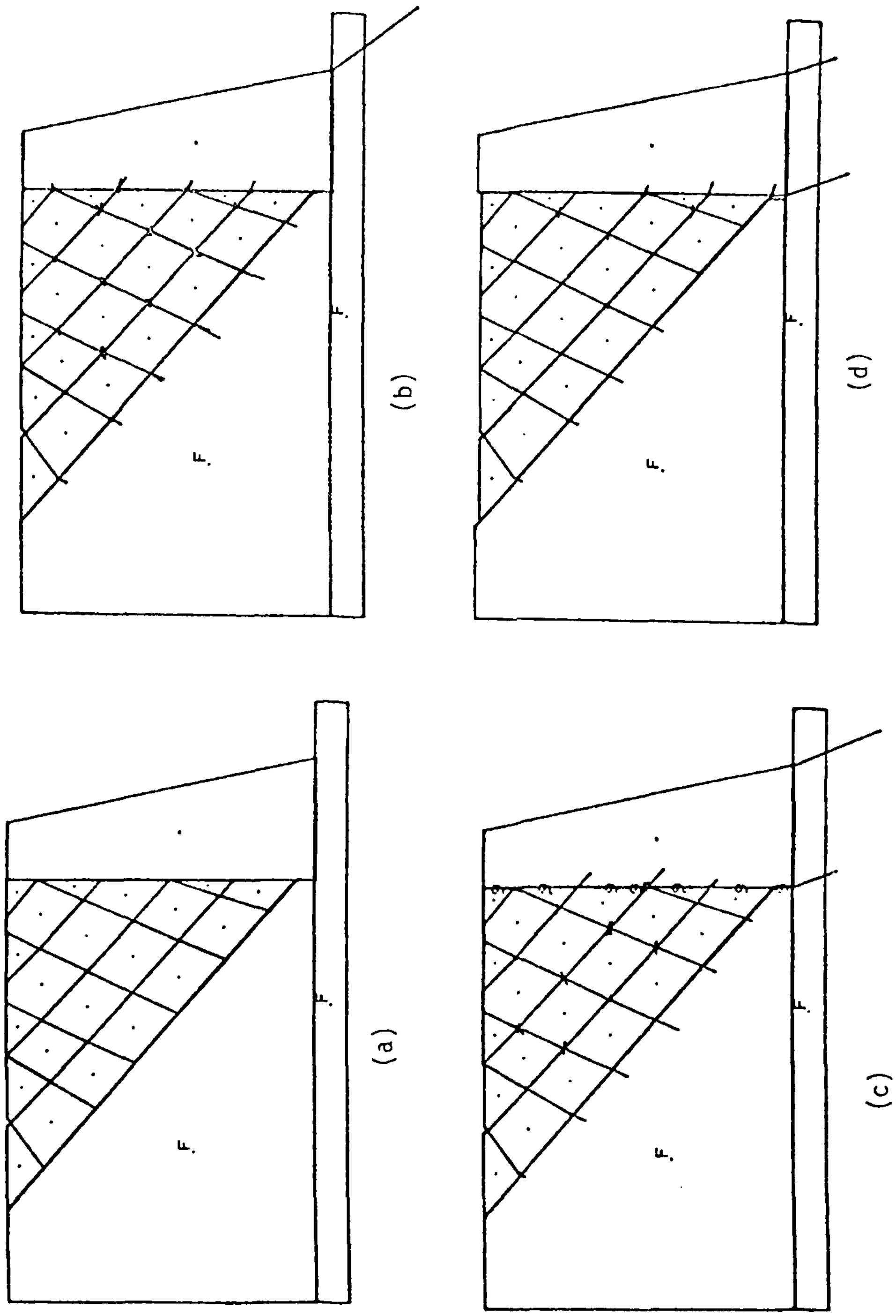
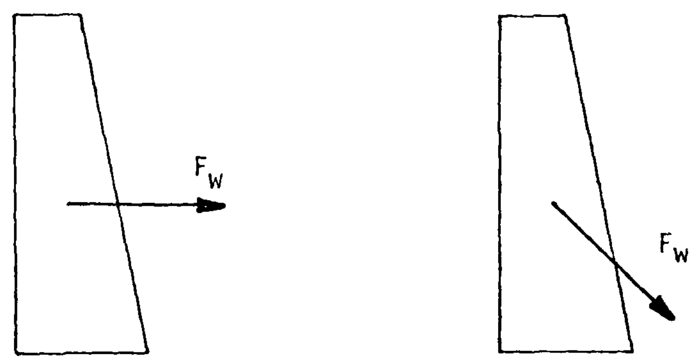



Figure 2.3  A gravity retaining wall

case is not stable - note the settlement of the mass and the gap at the lower left hand corner of the wall. Failure has occurred because sufficient resistance could not be developed along the base of the retaining wall. Also, the reduction of the frictional resistance between the mass and the wall reduced the overturning moment on the wall which in the previous cases had acted to increase the shearing resistance along the base of the wall. This is easily understood in terms of a simple analogy - trying to move the retaining wall by a single force acting through its centroid.




The two sketches represent the extremes in terms of orientation of contact forces along the wall. In the first sketch, representing the case $\phi_w = 0$, the force exerted by the mass on the retaining wall, $F_w$, has no vertical component while in the second sketch, representing the case $\phi_w = 45°$, the force exerted by the mass on the retaining wall, $F_w$, has a vertical component. The vertical

component of $F_w$ acts to increase the normal force on the base of the retaining wall, thus increasing resistance to sliding movement. The effect of increasing the coefficient of friction $\phi_w$ is thus to stabilize the retaining wall against translational sliding.

Example 4 - A Rock Slope Which Fails by Toppling

The assessment of the stability of a cut slope in light of translational kinematics often makes use of the fact that if the major joint set dips into the slope, failure by sliding is not possible. Although this statement is true, the fact that a rock mass meets this criterion does not automatically ensure the stability of the cut slope as this example illustrates.

Presented in Figure 2.4 are several stages of the progressive failure of a cut slope where the major joint set dips into the slope face. Figure 2.4(a) represents the case before running the program while Figure 2.4(b) illustrates the situation just as failure begins; as can be seen from the figure, the toe block must move before the mass can fail. Thus the toe block represents a "keystone" and in the absence of fracturing, the behavior of the entire mass depends upon the behavior of this block. Any remedial action designed for a cut such as this must be based upon knowledge of which blocks or sections of the slope act as keystones. With the Distinct Element method it is a simple matter to determine which blocks can best be utilized to stabilize the mass.

Figure 2.4(d) illustrates another physically observed feature which is accurately modeled by the Distinct Element method. After

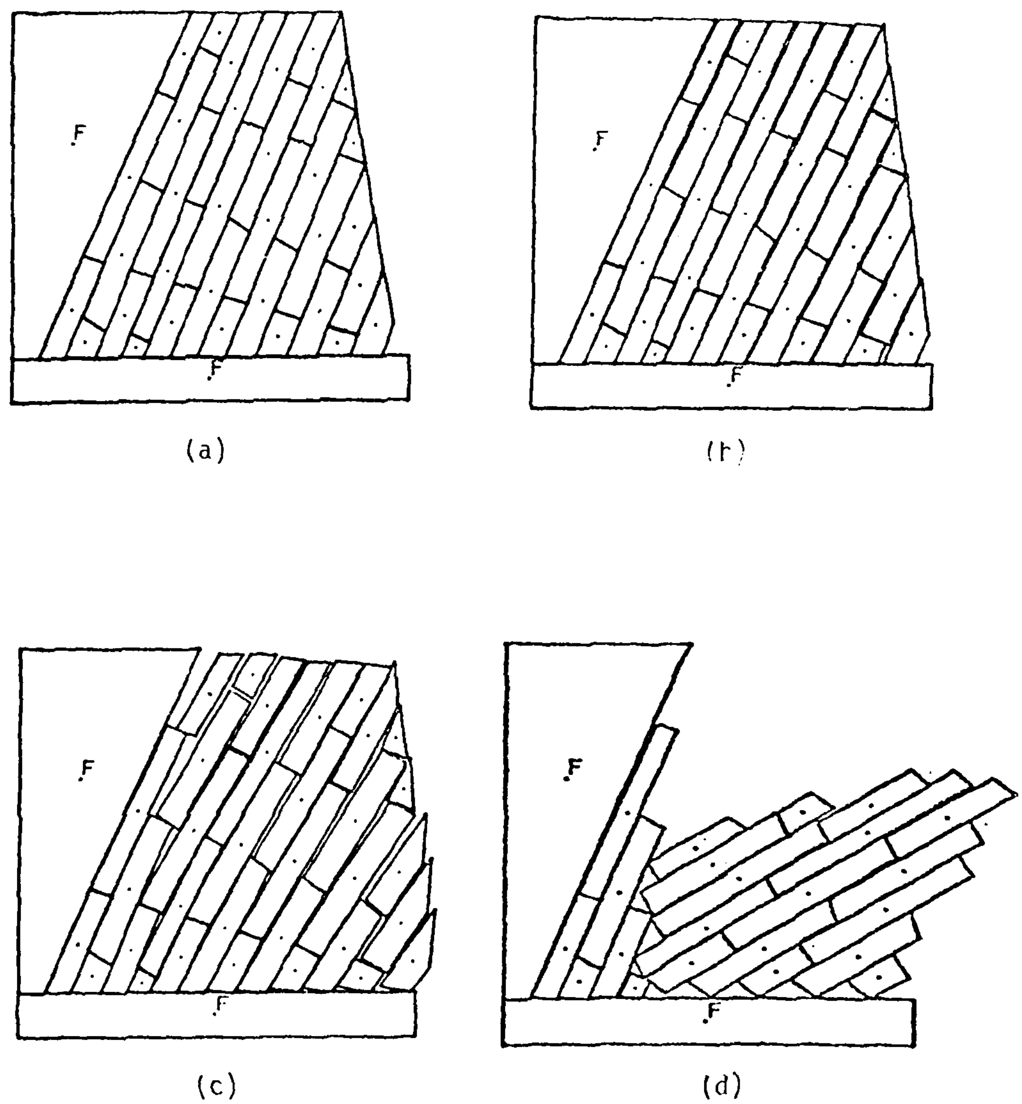



Figure 2.4 A rock slope which fails by toppling

a significant amount of movement has occurred, stable equilibrium of the mass is reached. (Blocks which moved away from the mass were erased as the program progressed).

Example 5 - Anchoring a Large Force in Rock Mass

This example presents a comparison of the failure loads calculated when a large external force, such as an anchorage force for a transmission tower, is applied to a jointed mass in two different directions. The rock mass in question and the two loading directions are illustrated in Figures 2.5(a) and 2.5(c). The force vectors which cause failure, drawn to a common scale, are also illustrated; the deformed geometries are illustrated in Figures 2.5(b) and 2.5(d).

If the scale of the problem is such that the bedding planes are spaced at three feet, the visible jointing is spaced at six feet, the jointing parallel to the plane of projection is spaced at five feet, and the mass density is 160 pcf; then the failure loads are approximately 160 kips for the case where loading parallels the jointing, and 230 kips for the case where loading crosses the jointing.

The modes of failure are also markedly different in the two cases. In the case where the loading parallels the jointing, failure of the mass occurs essentially by slip along the joints. However, in the situation where the loading crosses the jointing, failure encompasses a larger volume of the rock mass and is more of a rotational failure than a slippage failure.

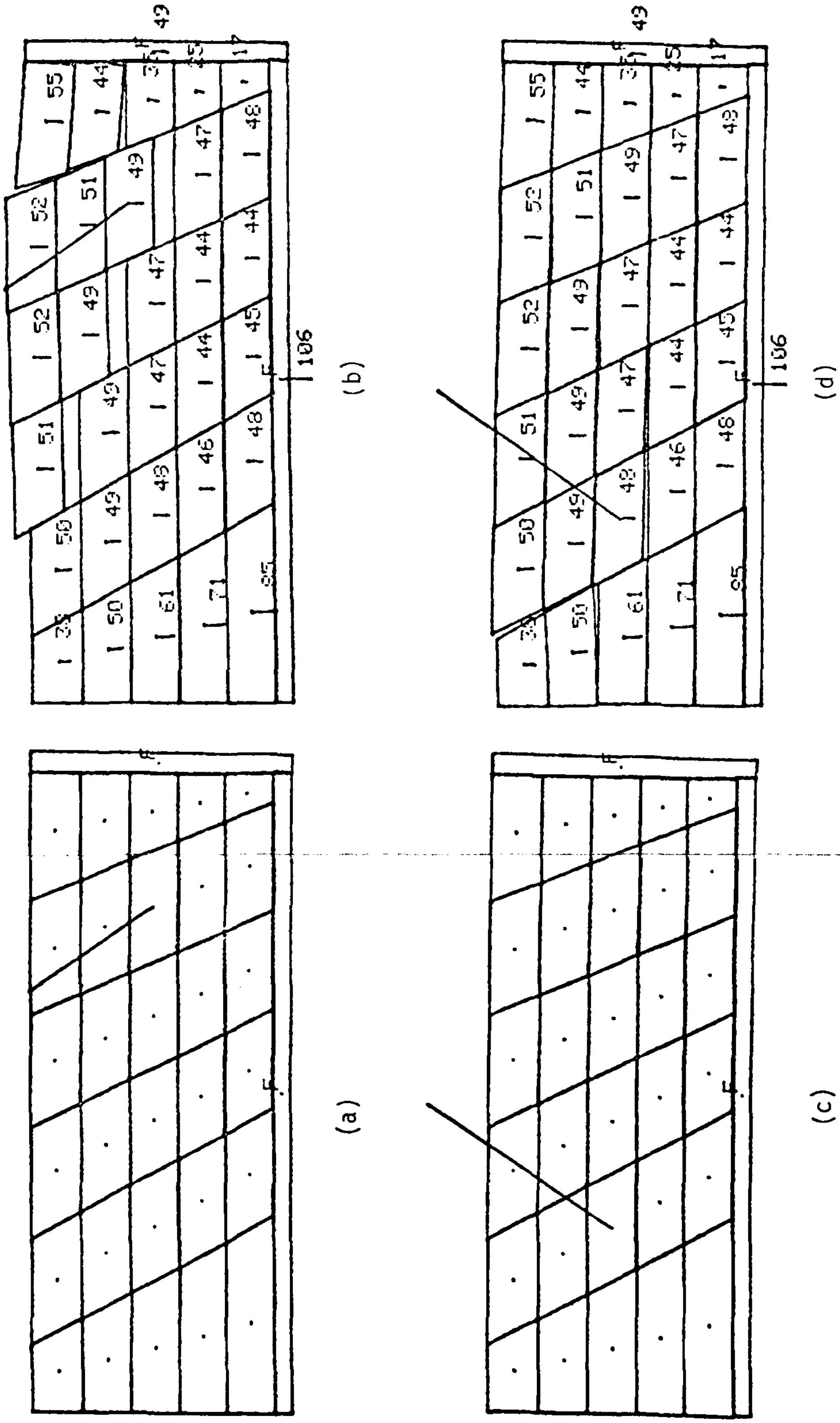



Figure 2.5  Anchoring a large force in a rock mass

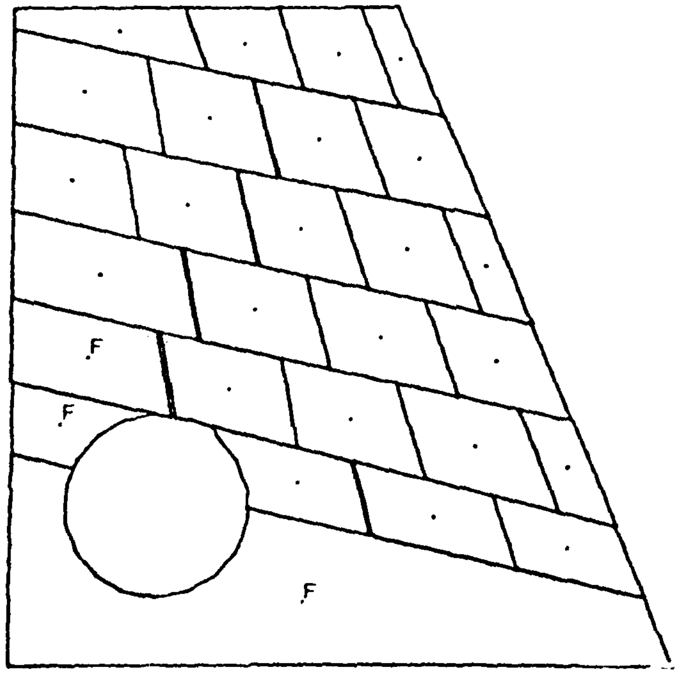
Example 6 - A Pressure Tunnel Near a Free Surface

This example examines a hypothetical situation where a pressure tunnel is located near a free surface. A situation such as this could be encountered, for example, in a diversion tunnel for a dam.

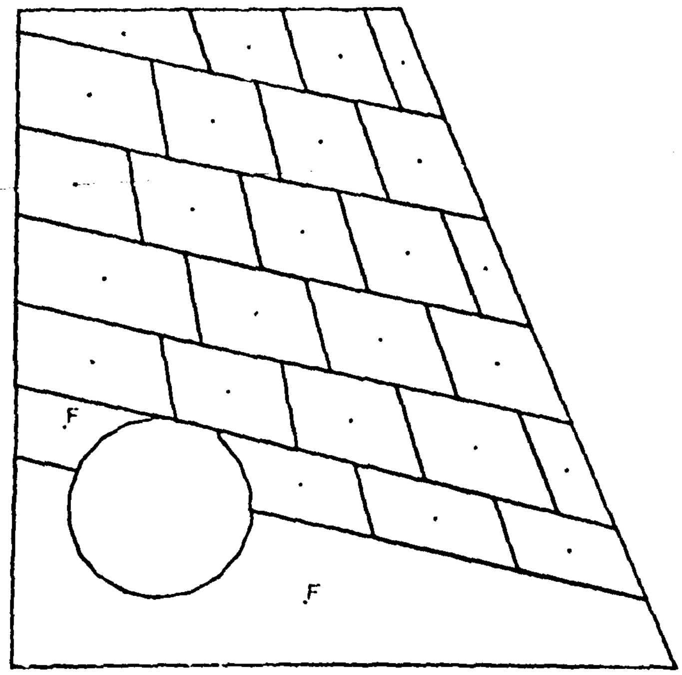
The failure of the rock mass in this particular case depends upon the penetration of water into the joints at fairly high pressures. Hopefully, in a real situation, water pressure testing would have been performed to assess the permeability of the mass and appropriate remedial action such as grouting and lining undertaken to prevent water loss. Nevertheless, the example is instructive and is presented in spite of its lack of realism.

Figure 2.6(a) illustrates the tunnel under consideration; the diameter of the tunnel is 20 feet and the internal pressure, which is assumed to penetrate all joints intersecting the tunnel, is 100 psi. The initial failure with the friction angle equal to 22 degrees on the joint planes is illustrated in Figure 2.6(b). In this type of problem the water pressure does not decrease as the joints open, for there is a practically unlimited supply of water to move out into the joints as they open.

Figure 2.6(c) shows a later stage of the progressive failure while Figure 2.6(d) illustrates the pressure distribution in the joints as indicated by an asterisk on those joints where water pressure is applied. The water pressure units illustrated are internal computer units and are seen to follow a parabolic trend, decreasing in intensity from the tunnel to the free surfaces. The

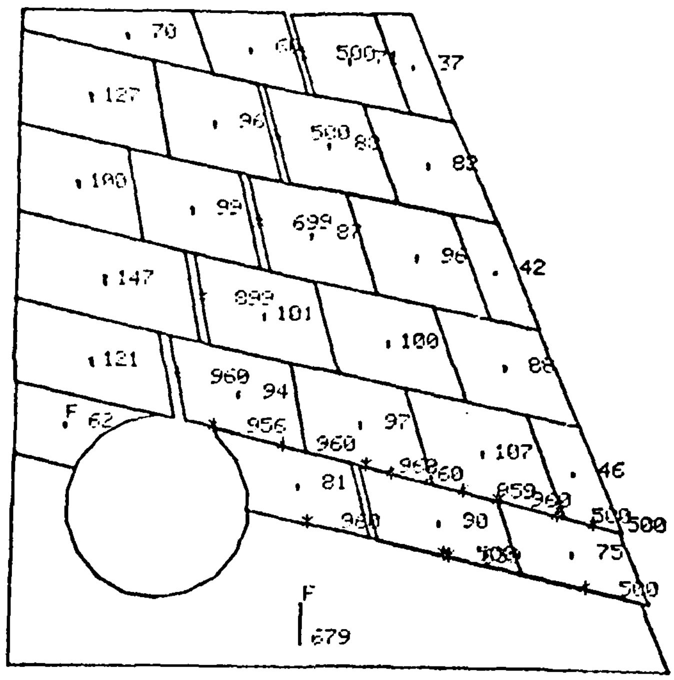



(b)

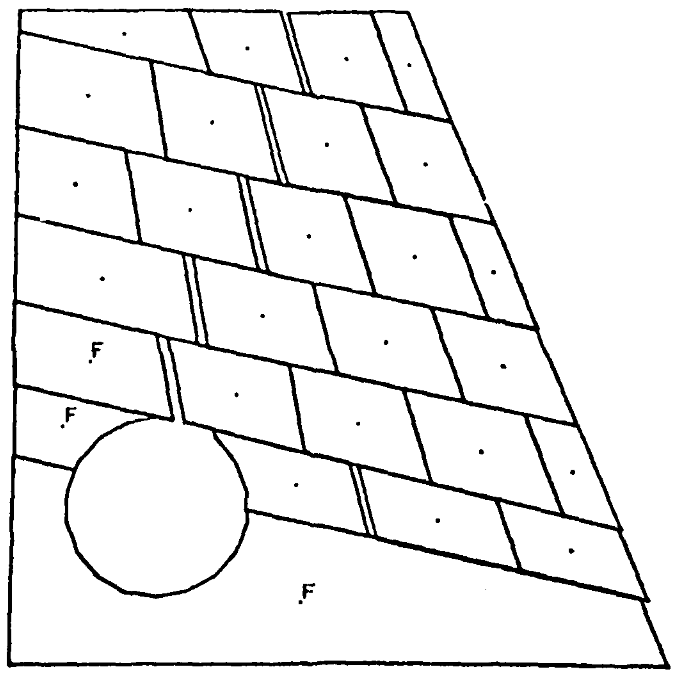



(a)

Figure 2.6 A pressure tunnel near a free surface




(c)




(d)

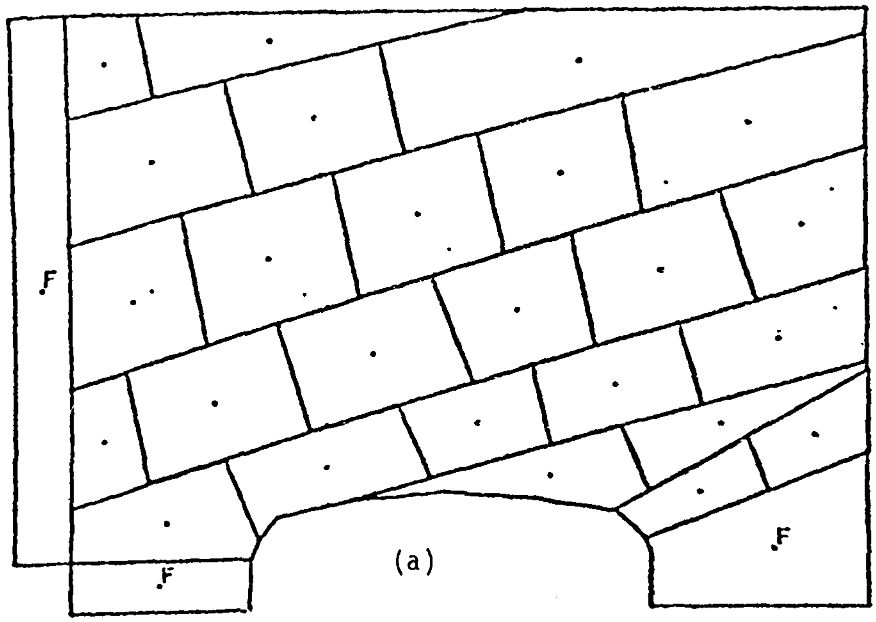
Figure 2.6 Continued

chosen pressure distribution has led to an unexpected displacement field as evidenced by the open joint one block away from the tunnel in the first row of blocks. Evidently, the effects of the free surface and the water pressure were sufficient to cause movement of the two righthand blocks in the first row of strata but, owing to the increased overburden load, the block nearest the tunnel remained stable.

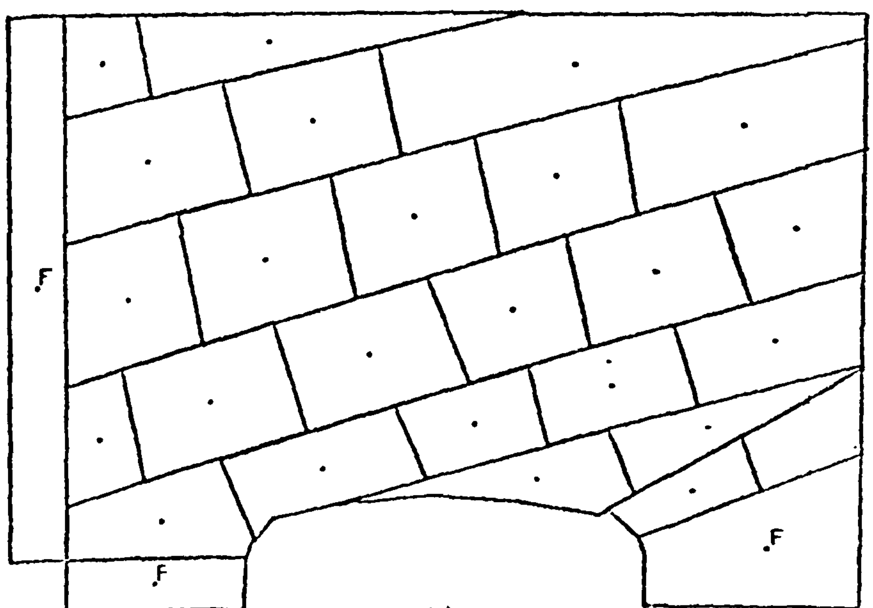
Example 7 - A Shear Zone in a Tunnel Roof

Example 7 is concerned with a problem of roof stability in a tunnel intersected by a plane of weakness having a noticeably lower friction coefficient than the rest of the mass and dipping at a less favorable orientation than the main joint set. In addition, the plane directly above the main failure plane was also assigned a low friction coefficient to better model a shear zone.

The tunnel under consideration has a width of 24 feet and is illustrated in Figure 2.7(a); the planes considered as the boundaries of the shear zone are assigned friction type 5 ($\phi = 5^\circ$) as indicated in Figure 2.7(d). The mode of failure, which can be compared to squeezing material into the excavation by movement along the planes defining the shear zone, is illustrated in Figure 2.7(b) and 2.7(c). The disruption of the integrity of the roof defines a volume of rock which must be restrained by the support system. At a unit weight of rock of 160 pcf, the weight of this volume of rock is approximately 100 kips per foot of tunnel length.




(a)




(b)

Figure 2.7  A shear zone in a tunnel roof

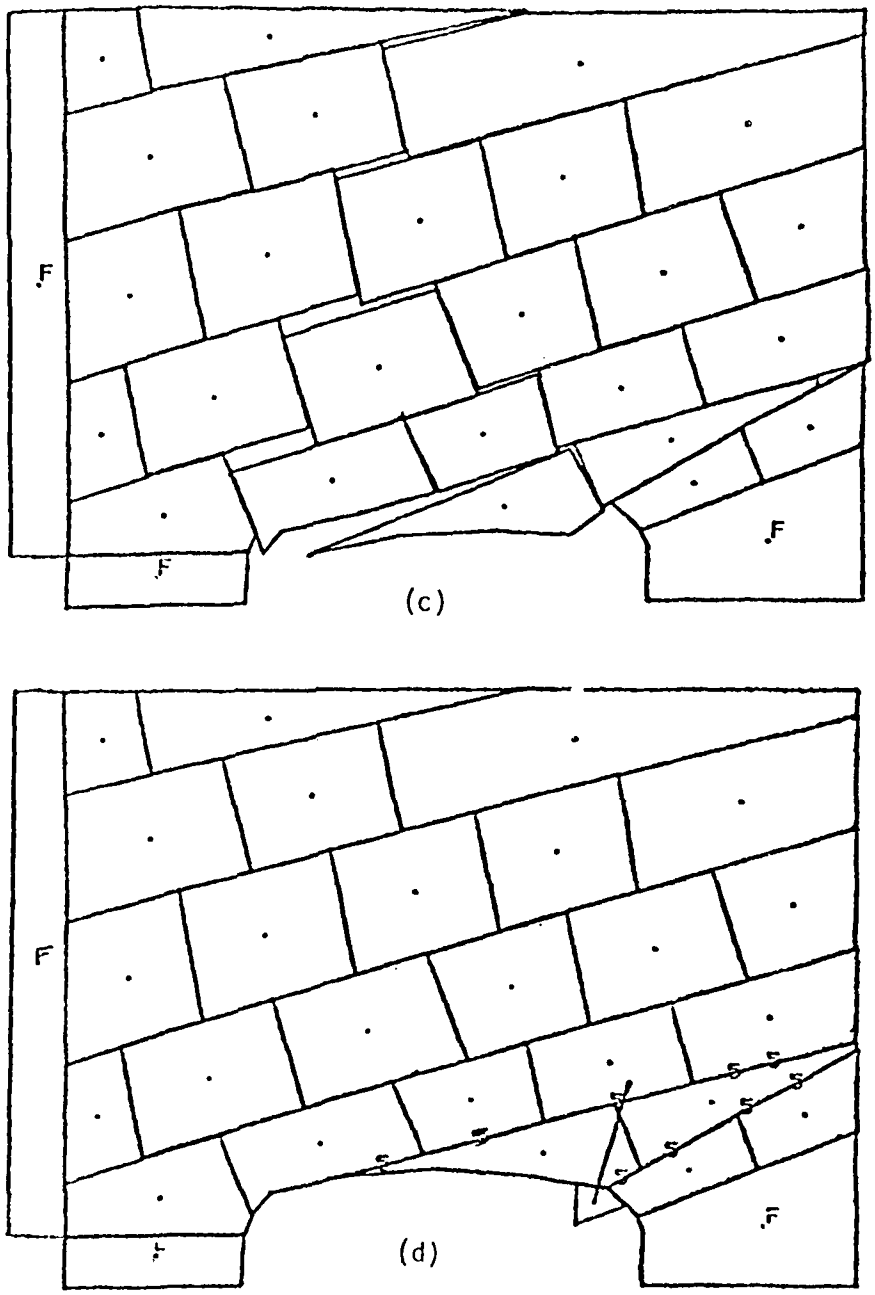



Figure 2.7 Continued

Recognizing that the block exposed in the upper right hand corner of the tunnel acts as a keystone upon which the behavior of the roof depends, the force necessary to stabilize this block (and thus the entire system) was determined. By placing a small block in contact with the desired block and applying various forces it is possible to determine the force that will maintain equilibrium of the mass. The forces could equally have been applied at the centroid of one of the failing blocks, but by utilizing a small block acting along the edge of one of the failing blocks the effects of rotation due to eccentric loading are better modeled. One such force is shown in Figure 2.7(d). This force, which has a magnitude of approximately 20 kips per foot of tunnel length demonstrates that it is possible to keep masses in equilibrium with forces that are small when compared to the weight of the mass which is failing.

Example 8 - Behavior of a Jointed Mass During Mining by Caving

The final example presented in this section illustrates the movements of blocks and the forces developed during these movements as progressive failure occurs in a large, jointed mass being mined by caving techniques. The block configurations as mining progresses are illustrated sequentially in Figures 2.8(a) through 2.8(j). The figures present the situation beginning some time after mining had commenced; in addition, as soon as individual blocks had moved sufficiently far from the mass so that they no longer influenced the behavior of the mass, they were erased. In

other words, the problem of jamming or arching at the draw point was not considered.

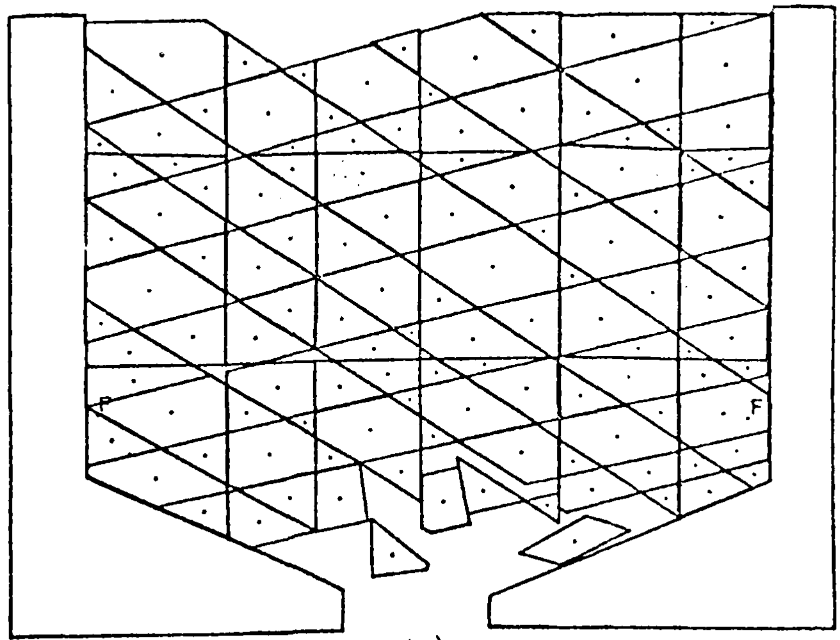
After the first two introductory illustrations (Figures 2.8(a) and 2.8(b)) alternate illustrations show only the contact forces, for the block outlines would only make the drawing more difficult to interpret.

The factors that influence the behavior of the mass include a relatively low friction angle on the joint planes ($\phi = 17^\circ$) and rigid boundaries. The four independent, intersecting joint sets are not claimed to be representative of conditions at a particular mine site. Rather, they were selected solely to give the mass more freedom to move, as two intersecting joint sets were found to have a tendency to lock and stabilize as the individual blocks moved.

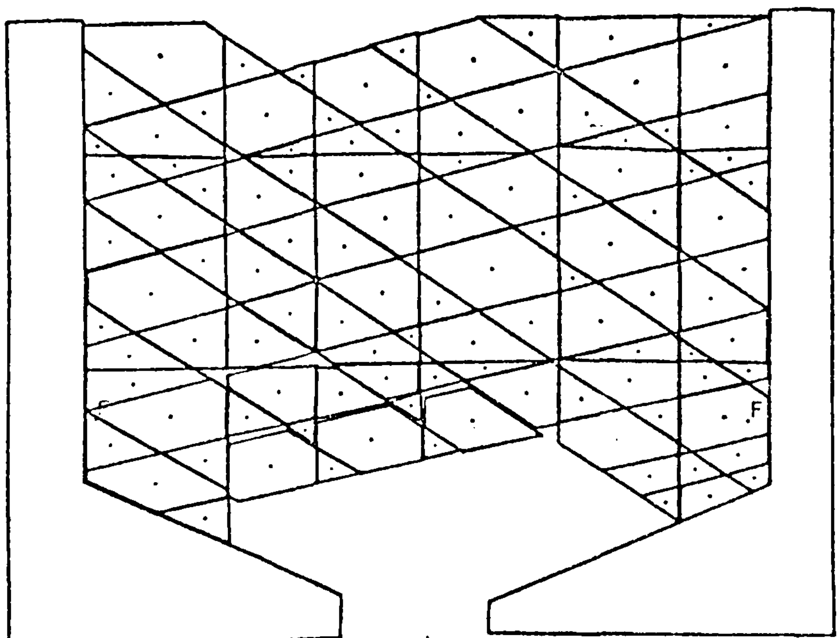
Examination of Figures 2.8(a), 2.8(b), and 2.8(c) illustrate the expected movement of the lower unconfined blocks. Figure 2.8(d) illustrates that two separate arches have developed, indicating that the blocks in the lower part of the mass are failing as a unit and, judging from the magnitude of the forces in the upper part of the mass, providing enough resistance to keep the upper part of the mass stable.

This conclusion is reinforced by Figure 2.8(e) where it can be seen that the lower blocks are separating significantly from the mass. Figure 2.8(f) shows the continued development of two separate arches. The thrusts developed in the lower arch are not of sufficient magnitude to stabilize the mass, as evidenced by the progression of raveling up into the mass as illustrated in

Figure 2.8(g) and the collapse of the lower arch as shown in Figure 2.8(h). Figure 2.8(i) illustrates the continued movement of the mass toward the draw point. The uppermost layer is still maintaining its integrity due to the slight confining effect at the arch abutments. The lower arch has completely failed as can be seen in Figure 2.8(j). Although not illustrated, the upper arch eventually collapsed when a sufficient movement of the lower mass blocks caused a loosening at the arch abutments.

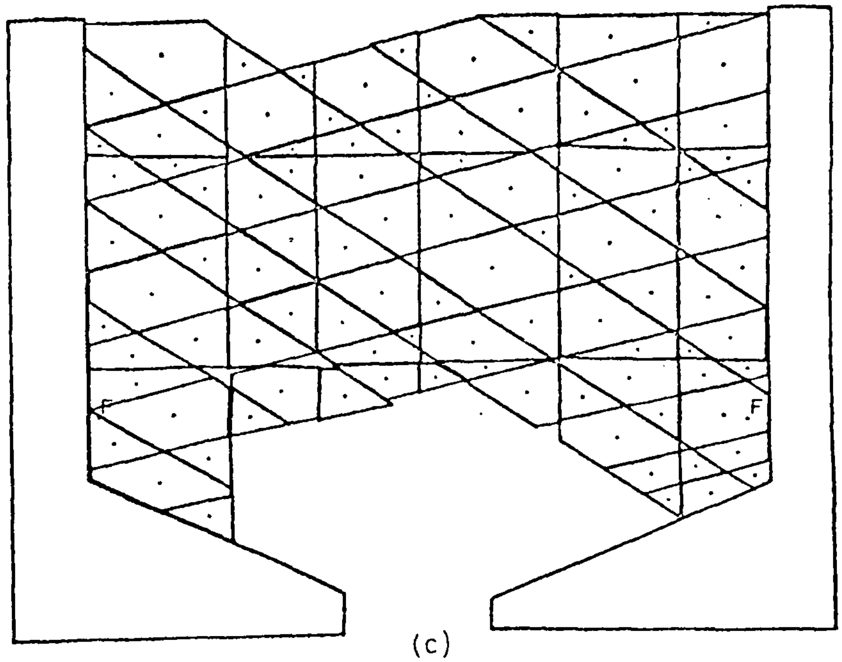



(a)




(b)

Figure 2.8 Behavior of a jointed mass during mining by caving

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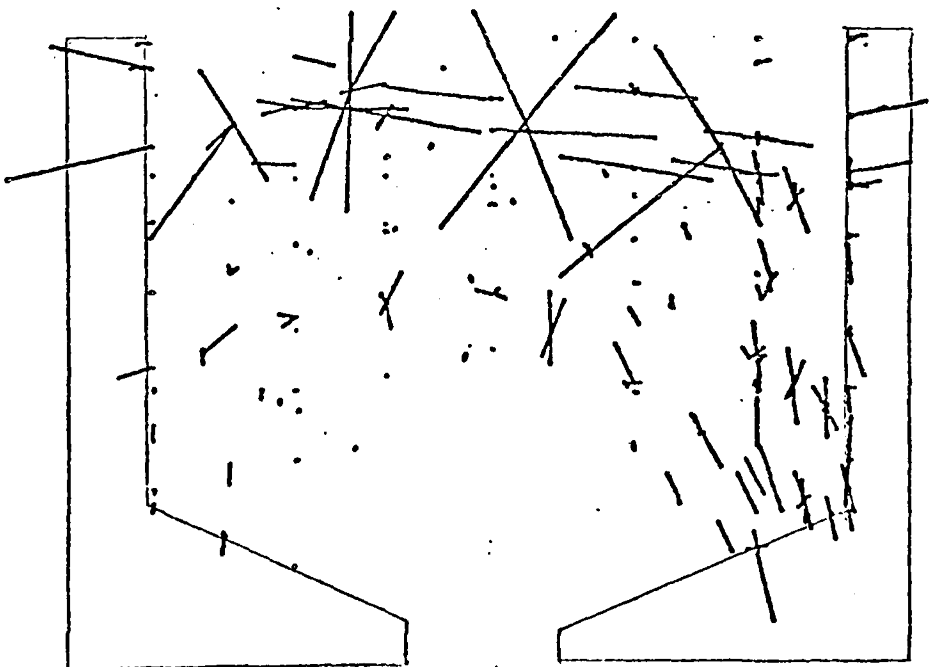

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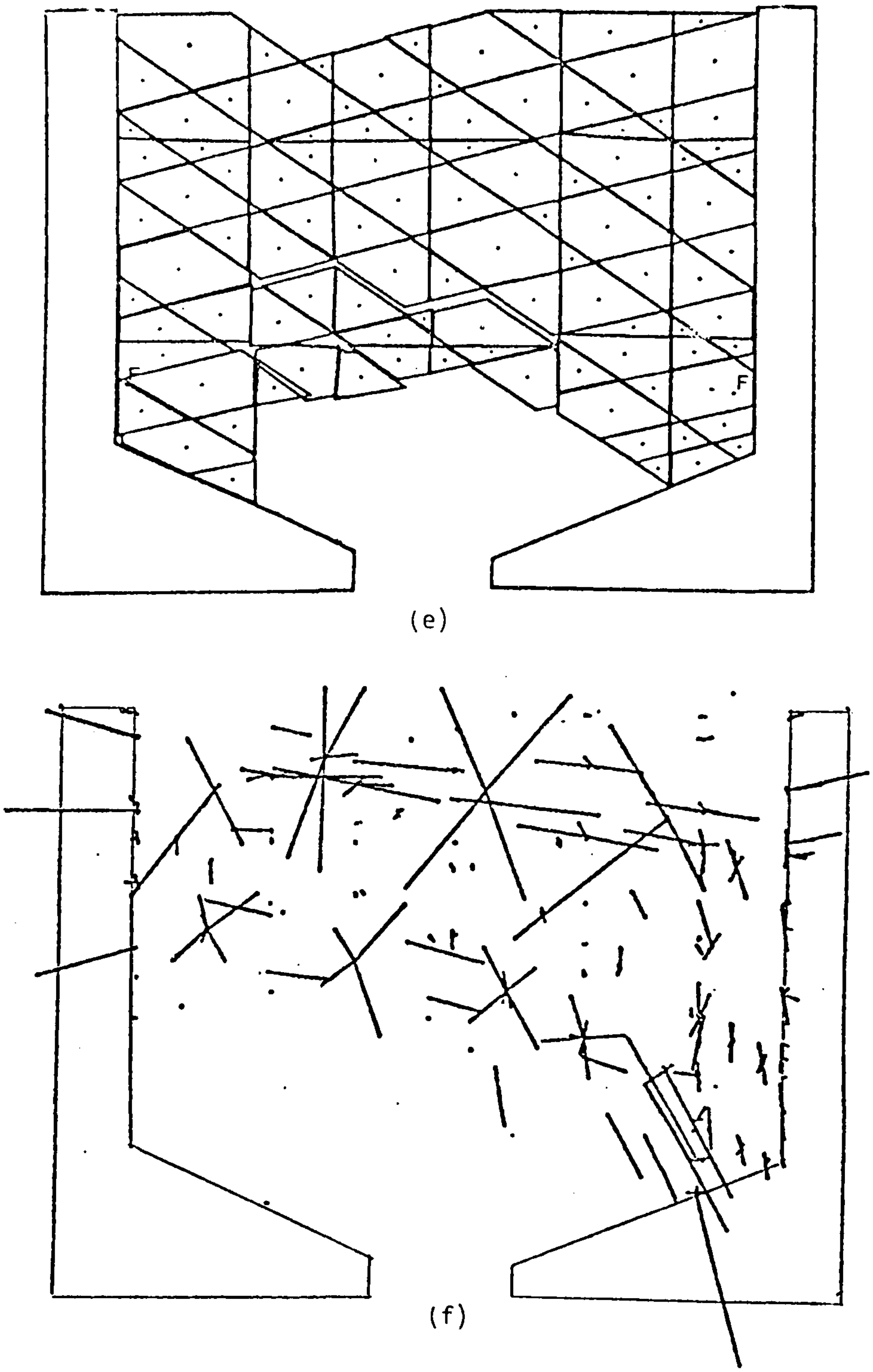
Figure 2.8 Continued

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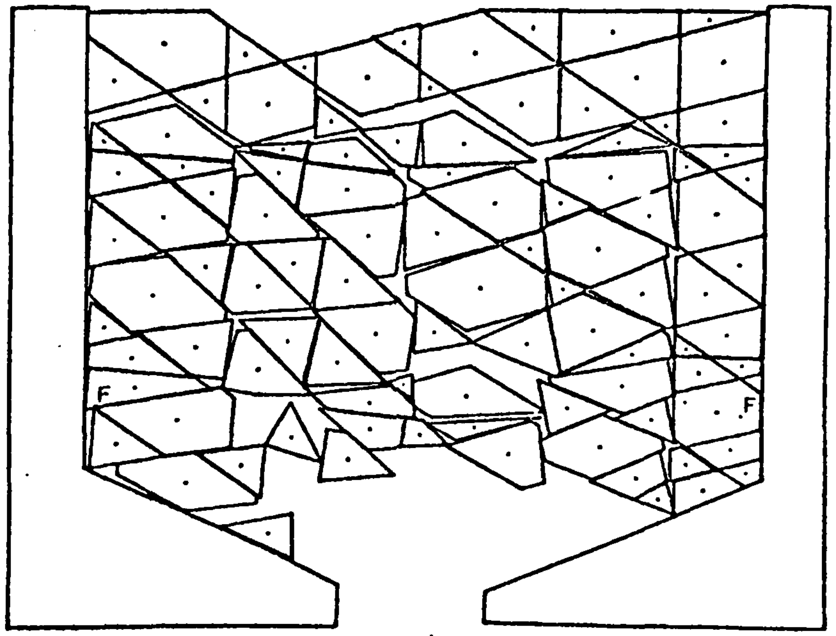


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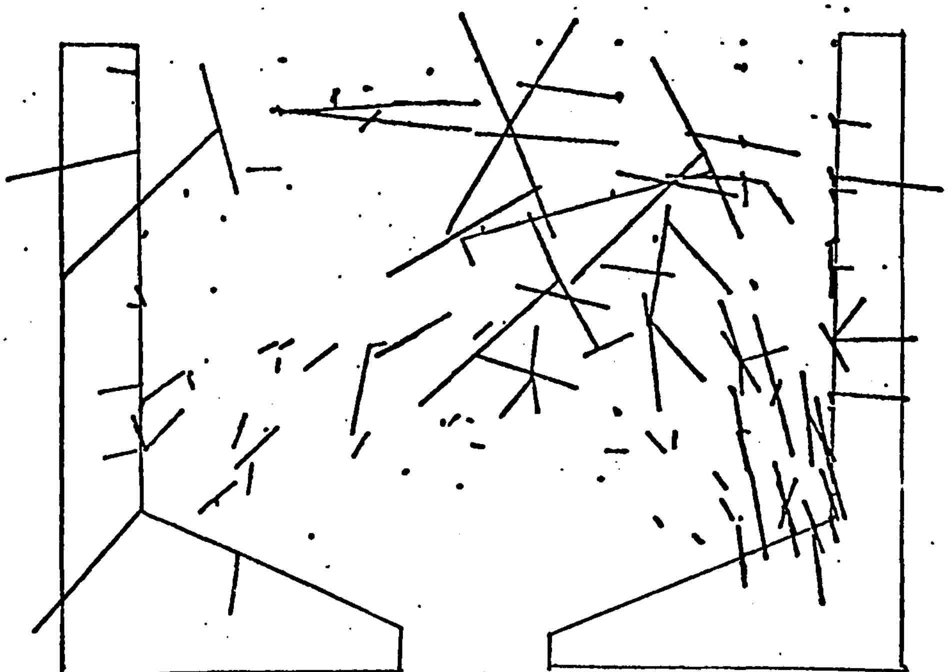

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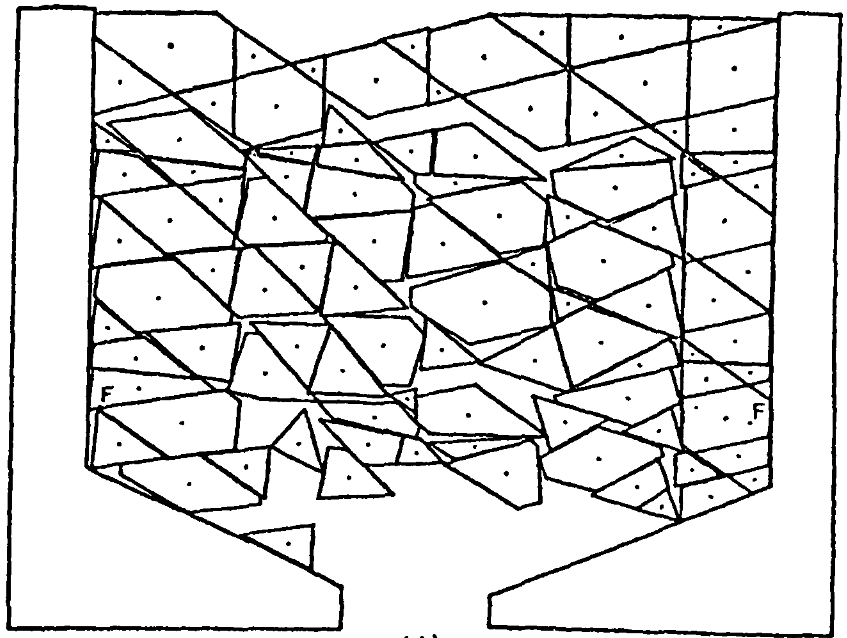
Figure 2.8  Continued

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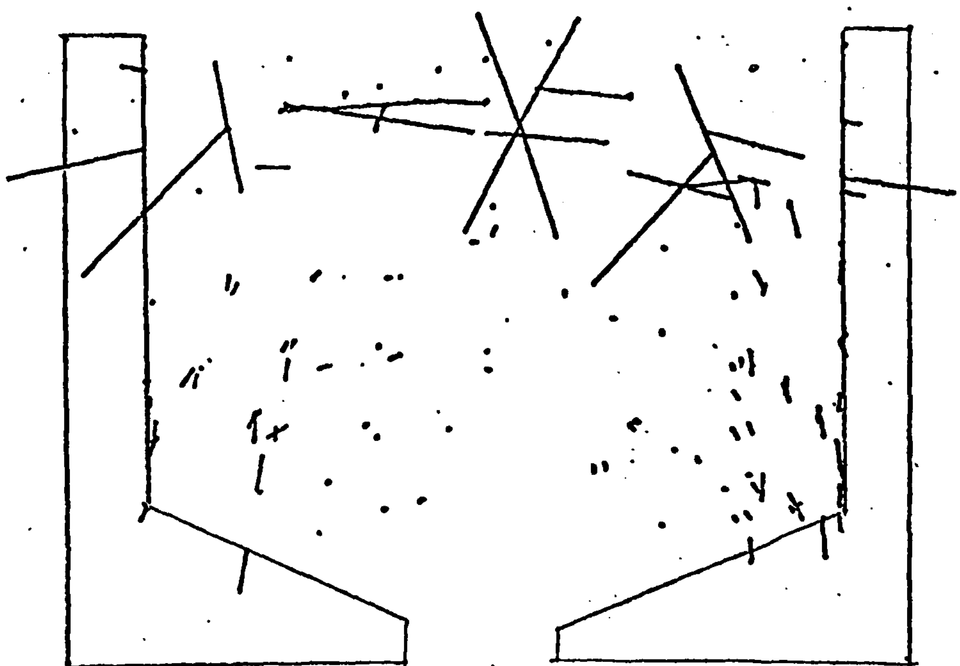

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Figure 2.8 Continued

# CHAPTER III

# VERIFICATION OF THE ACCURACY OF RESULTS CALCULATED BY THE DISTINCT ELEMENT METHOD

## 3.1 Introduction

As the Distinct Element method is, in fact, an approximate method to obtain the response behavior of a block jointed system, an attempt must be made to verify that the calculations performed in the method yield results that are acceptable. What is required of a solution to a problem involving the inclusion of joints in a rock mass is that it incorporate and assign most influence to the significant parameters affecting the behavior of the mass. If in doing so, some small elastic strain is overlooked, the solution cannot be classified as exact but, needless to say, if the important responses of the block system are modeled correctly, the solution certainly must be classified as acceptable.

Confidence in the use of an approximate numerical technique such as the Distinct Element method can best be developed through comparison to existing solutions to problems which include the significant parameters which the numerical technique models. A high degree of confidence is obtained if the numerical model duplicates the results of proven analytical solutions. Somewhat less confidence in the model is developed if the comparisons are made to approximate solutions, although the degree of confidence in the approximate solutions, as evidenced by their level of acceptance by practicing engineers and designers, obviously must

be considered in the comparisons.

The problem of verifying the accuracy of solutions calculated by the Distinct Element method is compounded by the lack of analytical solutions that describe the behavior of a jointed rock mass. Instead, when dealing with the behavior of a jointed mass, most analytical solutions invoke approximations which draw upon empirically observed behavior models, soil mechanics theories and classical elastic solutions with the elastic parameters modified to reflect joint behavior. These types of models are severely limited in their applicability; for example, the elastic analyses are probably most valid for the case of very close jointing and the case of a very regular degree of jointing that can be characterized as an anisotropy. More general models for calculating the behavior of a jointed mass typically attack the problem by assuming simplified relationships between the parameters selected to typify the behavior. This type of model suffers in that the full implications of the roles these parameters play in the behavior of the mass are not yet fully understood.

What is needed then to perform a truly accurate comparison unfortunately does not exist. Rather, the very nature of the problem dictates that a choice be made between approximate techniques of analysis which often contain vastly simplified, empirically adjusted assumptions regarding the overall mass behavior which could possibly only be valid for a distinctly limited range of material properties.

One group of approximate techniques, which is limited in its

scope to geometrically ideal problems, is acceptable for a comparison of this type. Limit Equilibrium solutions are concerned with the static equilibrium of bodies at the point of failure. Under this assumption, the frictional forces are assumed to be fully developed and thus force diagrams can be drawn and equilibrium equations written. This method requires the knowledge of the location of the failure surface and a minimal number of interacting blocks. Provided that the geometry of the mass can be represented simply, Limit Equilibirum principles are routinely used to calculate the response of a jointed mass.

In the sections that follow, five simple approximate models for the behavior of jointed masses are presented and the calculated responses are compared to that generated by the Distinct Element method. Included in these models are Limit Equilibrium analyses of: one block on an inclined plane with sliding and rotation possible; two interacting blocks, one in an active state, the other in a passive state; and, multiple interacting blocks both with and without the possibility of rotation. Also included are comparisons to physical models examined with a base friction apparatus, presented primarily for qualitative observations on the kinematics of large displacements, as well as a simple pressure distribution in a jointed mass where simplifying assumptions regarding material behavior have reduced the problem to an application of the principles of static equilibrium.

Common to the models chosen for comparison to the Distinct Element model are simple geometric properties and minimal

assumptions regarding material behavior. As a result of this the models possess the additional feature that an intuitive insight into the ultimate response behavior is often possible. If it is possible to demonstrate that the simple models give the correct response, then it is much more meaningful if the Distinct Element model gives the same response.

## 3.2 The Base Friction Method

The base friction or base shear modeling technique is a physical, scale modeling technique described by Goodman (1972) that developed from the suggestion that the effect of gravity on a jointed rock slope could be simulated by shear forces on the base of the model as it was pushed over a plane surface. Alternatively, as in demonstrations attributed to Dr. E. Hoek (Goodman, 1976) the base may be moved while the model is restrained. The advantage of a horizontal assemblage of blocks lies in the fact that complex, unstable models may be constructed and failure observed as gravity is suddenly "switched on". Disadvantages arise due to the fact that accurate modeling of a real situation requires that a model material having the exact frictional properties of the real material must be found. In practice, exotic mixtures of flour, sand, salt and cooking oil are used to make a cuttable, semi-rigid modeling material. A material of this type has the advantage that discontinuities may be cut into it at arbitrary orientations; for the purposes of this investigation, however, as rigidity was of prime importance, 1 cm cubes of commercially available plexiglass were used to construct the models. The inability to orient discontinuities at arbitrary angles was not considered a severe liability in this investigation as the end result was simply to demonstrate qualitatively that the Distinct Element method would reproduce the expected modes of failure in several models where the failure modes were obvious. Figure 3.1 illustrates the small base friction apparatus used to study the behavior of the jointed models.

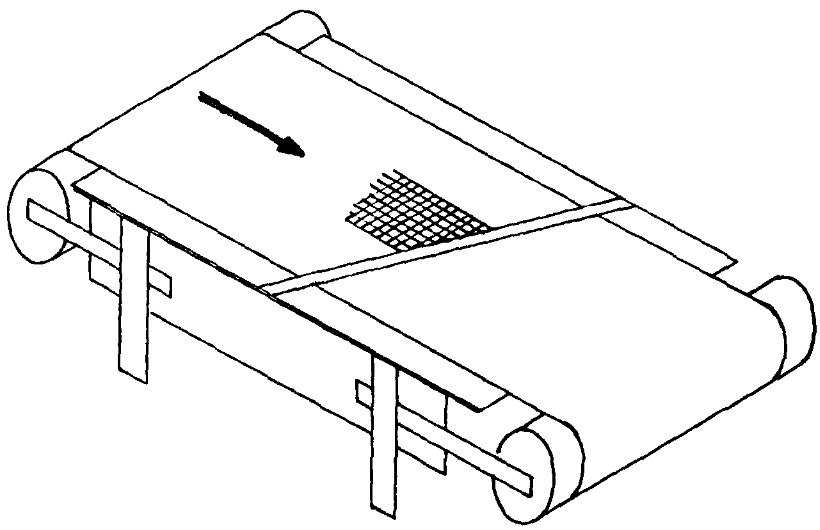


Figure 3.1 Diagramatic sketch of base friction apparatus used in comparison

Modeling techniques such as base shear are typically kinematic in that they reproduce the geometric features of the geologic structure and the excavation to a sufficient degree to establish possible modes of failure. However, they are not exactly scaled dynamically. For example, the base shear method does not give the correct response when a moving body acquires lateral momentum since in the base friction model, real accelerations are proportional to the driving belt velocity (Goodman 1976).

The implication of this is that in the absence of block to block contact, the only accelerations permitted in the model would be in the direction of the belt velocity as indicated in Figure 3.2. The Distinct Element model of this situation is included to demonstrate that momentum is indeed properly modeled.

However, several qualitative observations of a kinematic nature can be made: blocks which receive no supporting resistance must move downward under the effect of gravity; unconfined, geometrically unstable blocks must rotate and topple; and confined, geometrically unstable blocks must induce sliding in neighboring blocks as they rotate and topple. These three behavioral features of jointed systems can readily be simulated on a base shear apparatus by a laterally unsupported mine roof, an overhanging cliff and a cut slope in a jointed mass, respectively. These three failure models were chosen because, due to their simplicity, the kinematics of the failure are obvious. This makes them ideal for comparison with the Distinct Element method for it demonstrates that the Distinct Element method can calculate the proper failure mode for several situations for which the failure modes can be envisioned.

Figures 3.3, 3.4, and 3.5 illustrate a comparison of each of the three above mentioned failure modes by the base shear technique and the Distinct Element method. Little, if any, comment appears necessary other than to point out the similarity of the developing failure in all three cases.

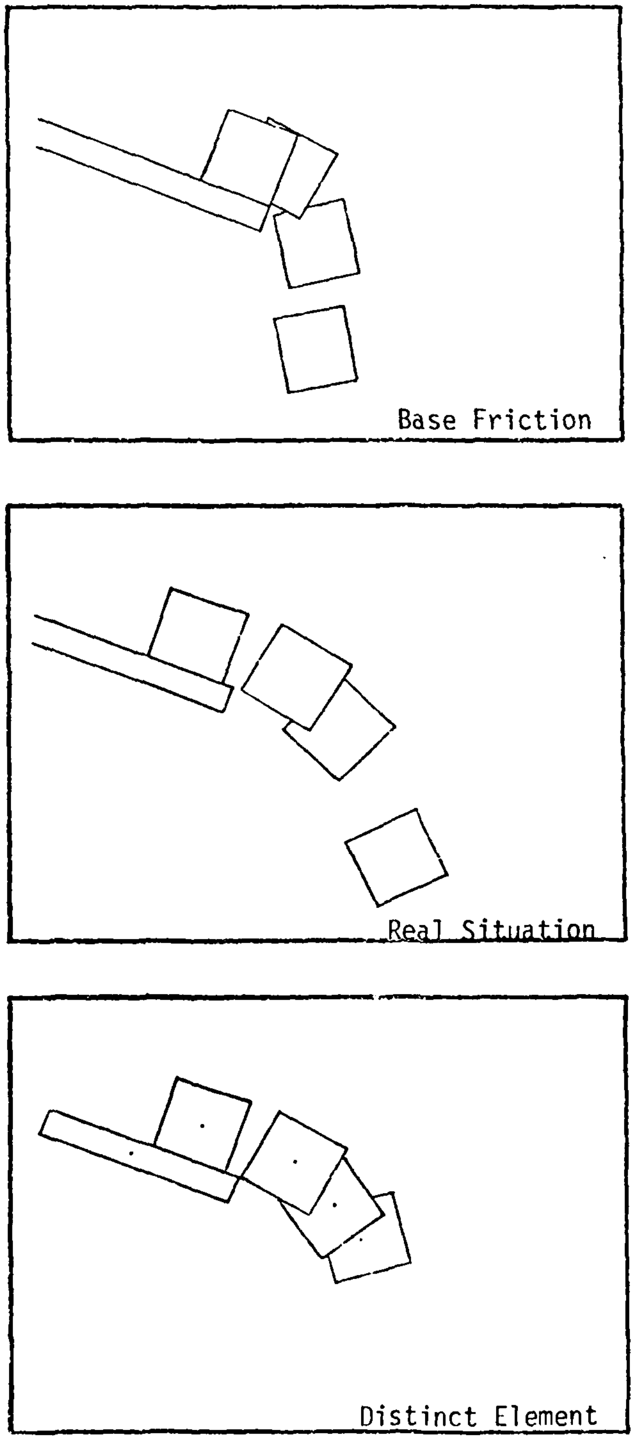



Figure 3.2 Dissimilarity of base friction model and Distinct Element method and real situation where momentum is not negligible.

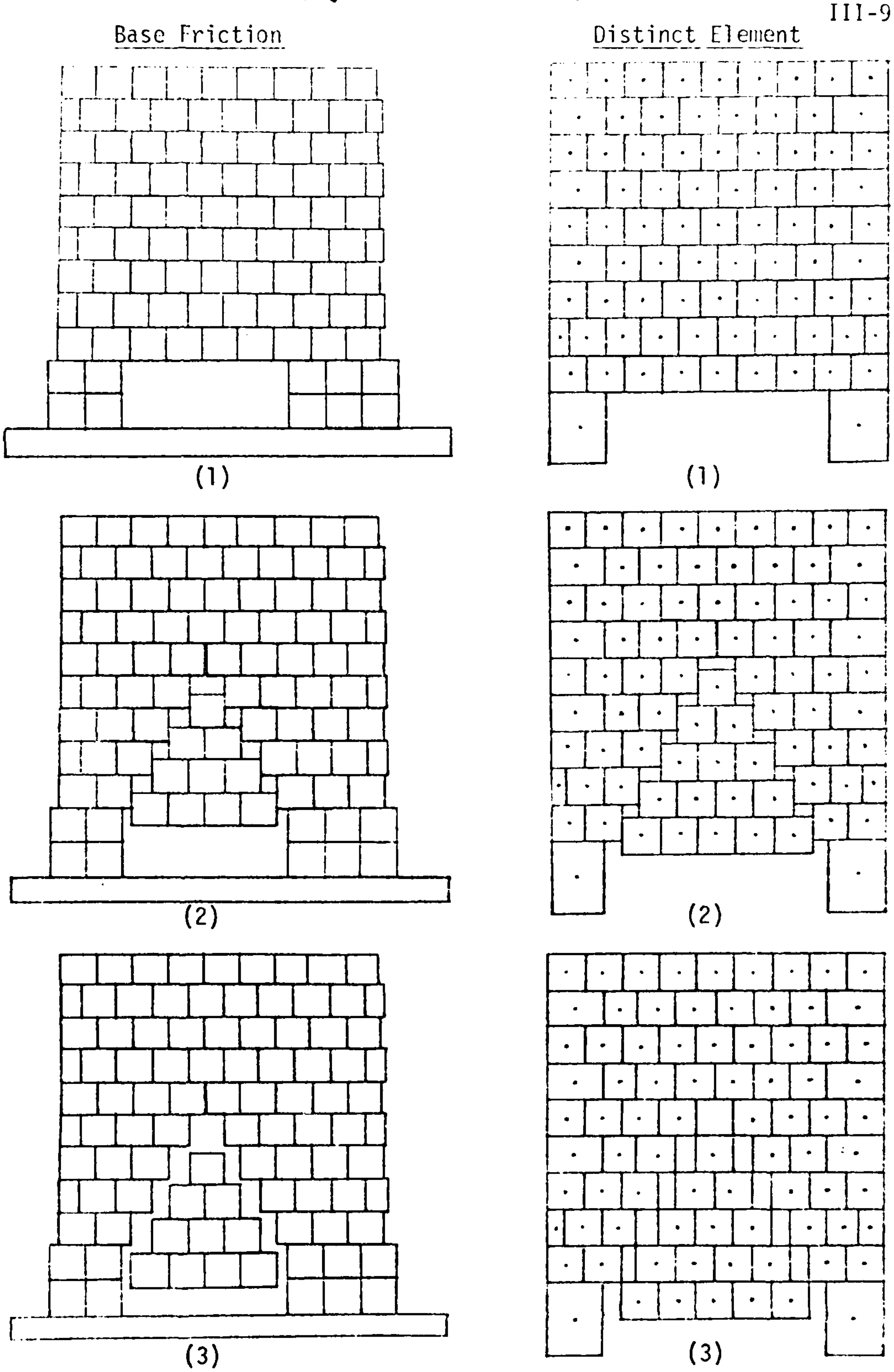



Figure 3.3 Comparison of base friction analysis and Distinct Element method for case of unrestricted, gravity induced block displacement.

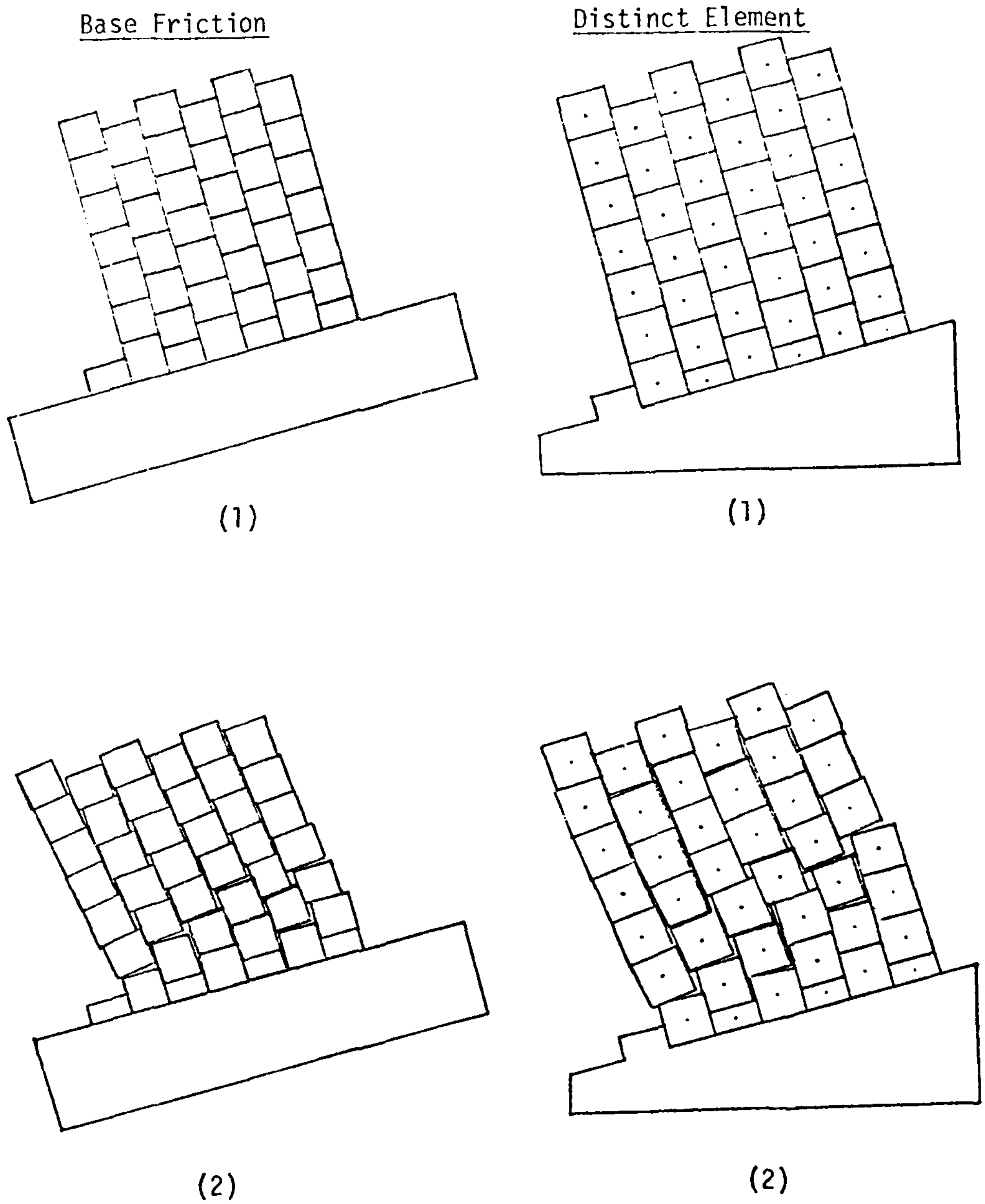



Figure 3.4 Comparison of base friction analysis and Distinct Element method for case of unconfined geometrically unstable blocks.

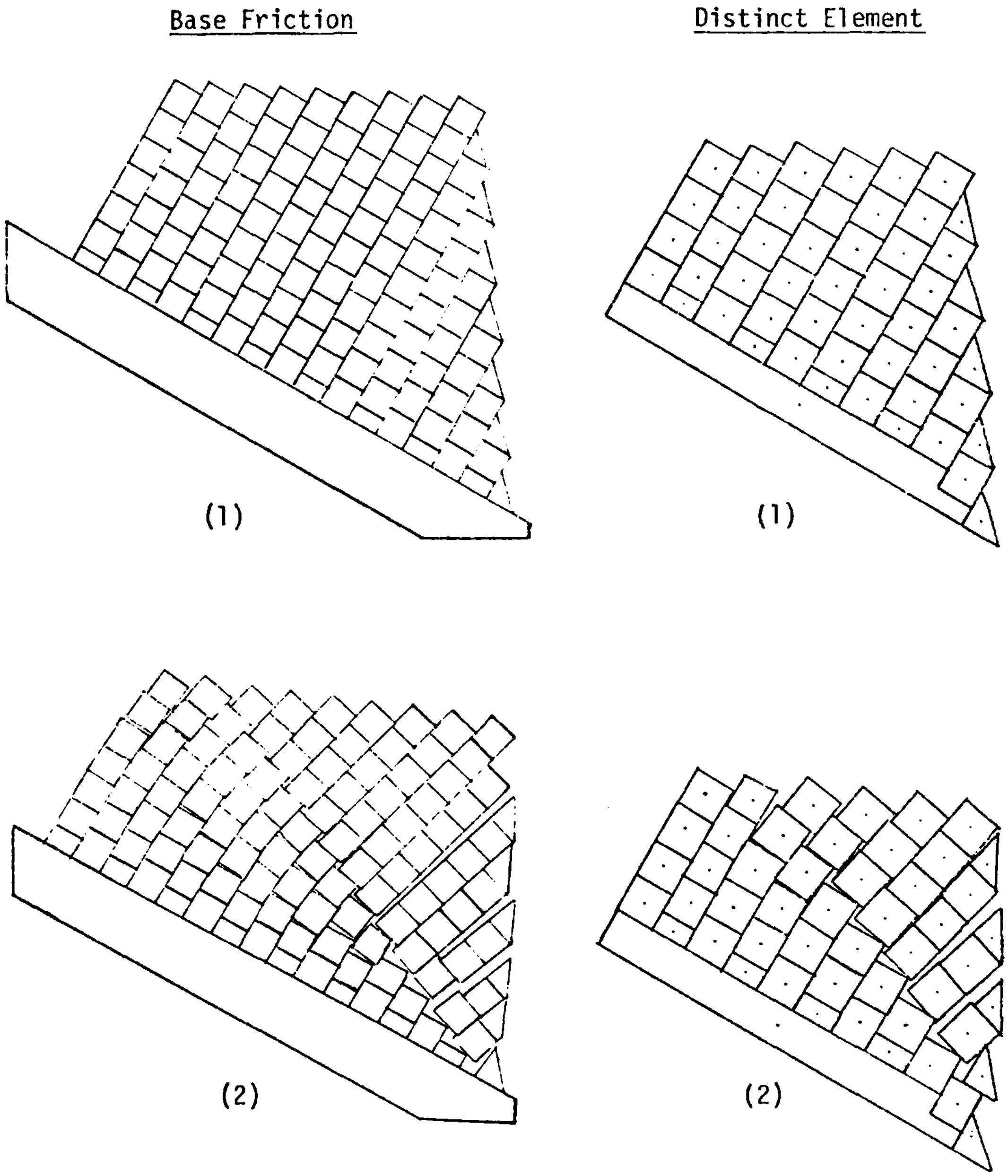



Figure 3.5 Comparison of base friction analysis and Distinct Element method for case of confined, geometrically unstable blocks.

### 3.3 Limit Equilibrium of a Single Block

The simplest and most obvious quantitative test of the validity of the Distinct Element method is whether or not it can adequately model the behavior of a single block on an inclined surface. The laws of static equilibrium furnish two important aspects of the behavior of such a block: first, it will not slide unless the angle of friction is less than the angle of inclination of the surface upon which it rests; and second, when the direction of the weight vector falls outside of the base of the block, overturning of the block must occur. This toppling stability is related to the geometry of the block as illustrated in Figure 3.6. When the ratio of the width of the base to the height of the block is less than the tangent of the angle of inclination, overturning of the block occurs.

Thus, the limiting stability condition of a single block on an inclined plane is a function of the angle of friction ($\phi$), the shape (ratio h/b) and the inclination of the sliding plane ($\psi$). The interrelationship of these parameters has been presented graphically by Hoek and Bray (1974) and is reproduced in Figure 3.6. This diagram delineates the four behavioral characteristics of a single block on an inclined plane: stable, sliding, toppling, and a combination of sliding and toppling. Note that the line $\phi = \psi$ is not fixed on the diagram - it is moved laterally to specify the boundary for a given $\phi$ situation.

The line $\phi = \psi$ and the line $h/b = \cot \psi$, representing limiting conditions for any specific block under consideration, suggest an

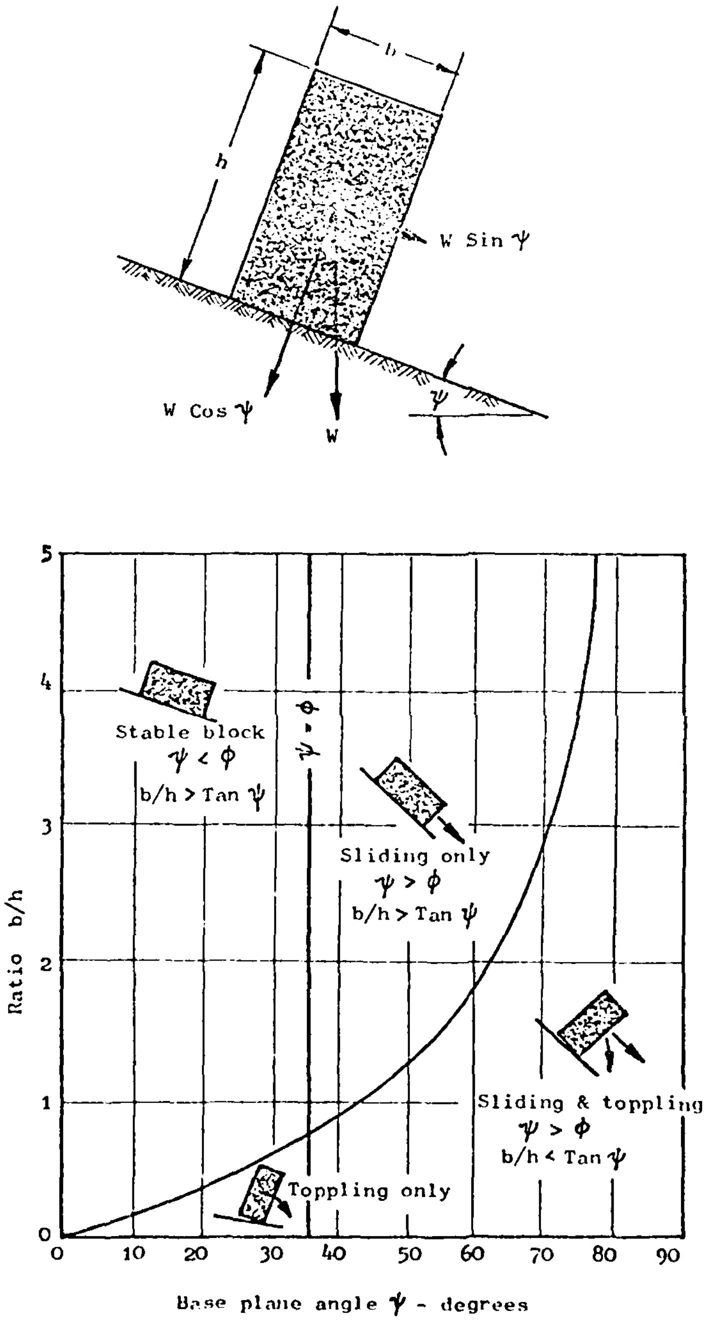
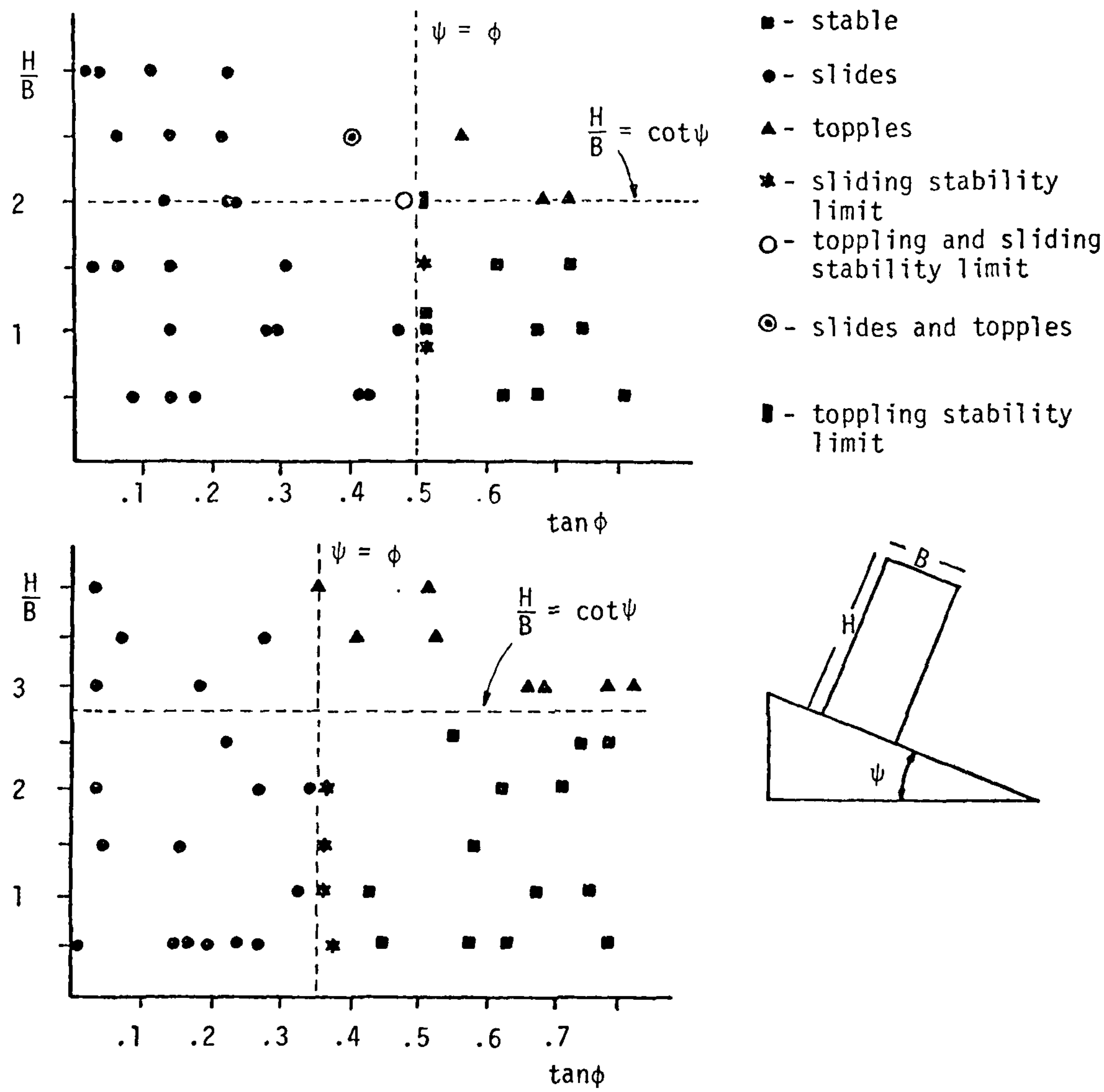



Figure 3.6 Conditions for sliding and toppling of a block on an inclined plane (from Hoek and Bray, 1974).

alternate method of plotting this data. For a given base plane inclination $\psi$, the geometric ratio (h/b) and the friction angle ($\phi$) are plotted as the ordinate and abscissa respectively. The line h/b = cot $\psi$ separates the plot into two regions in which toppling will or will not occur; the line $\psi = \phi$ similarly divides the plot with respect to sliding. The only advantage of such a plot, an example of which can be seen in Figure 3.7, is that the four regions are more nearly equal in area than on the Hoek and Bray plot. It suffers from the disadvantage that two lines must be drawn for each specific case whereas the Hoek and Bray diagram only requires that one line be redrawn.

As a test of the ability of the Distinct Element method to calculate the proper response of a single block on an inclined plane, paired values of $\phi$ and h/b were randomly generated for several different values of the base plan inclination ($\psi$) and the observed behavior of the block plotted on the described diagram. The results for two values of $\psi$ are presented in Figure 3.7. In addition, several limit values were plotted whenever possible. For example, in the case $\psi = 26.6^\circ$ the value of $\phi$ at which sliding just began was also noted. Also in the case $\psi = 26.6^\circ$, as the limiting condition for toppling was h/b = 2.0, limit conditions at which toppling just began were investigated.

The results presented in Figure 3.7 show that the Distinct Element method is capable of accurately predicting the behavior of a single block on an inclined surface with respect to sliding or toppling failures. However, close examination of the left side,




Notes
1) $\psi = \phi$ represents limit equilibrium for sliding
2) $H = B \cot\psi$ represents limit equilibrium for toppling

Figure 3.7 Limit Equilibrium conditions for a single block on a plane surface: $\phi$, H/B pairs randomly generated for constant $\psi$.

uppermost quadrant, indicates that most failures in this region were of a sliding nature rather than a combination of sliding and toppling. The reason for this is easily understood in light of the true meaning of the diagram.

The behavior of a sliding block is indeterminate except at conditions of limiting equilibrium; that is, the theory that has been used to predict the behavior of a block is only valid along the line $h/b = \cot \psi$ and along the line $\phi = \psi$. In three of the quadrants, the fact that either one or both of the failure criteria are not met still allows the determination of the behavior. Consider, as an example, the right side, uppermost quadrant: if a block cannot slide, rotational behavior can be deduced from moment equilibrium.

In the lefthand, uppermost quadrant however, neither of these stability criteria is met and the problem is highly statically indeterminate. Intuitively, it must be true that a block sliding on a frictionless surface cannot topple due to the inability of the system to develop an overturning couple. On the other hand, a block sliding on a plane inclined at an angle slightly greater than the friction angle experiences an overturning couple due to the frictional resistance acting on the sliding surface. If, additionally, the block geometry is conducive to toppling, then intuitively, the fact that the block is sliding should introduce an additional toppling moment. An analysis as simple as that illustrated in Figure 3.6 cannot predict the dynamic behavior just described as it is only concerned with limiting cases.

Examination of the plots in Figure 3.7 indicates that combined toppling and sliding was infrequently observed and only occurred near the limiting conditions. The line that delineates that area of the graph corresponding to simultaneous sliding and toppling behavior is not deducible from a simple Limit Equilibrium analysis. The fact that this coupled behavior is not determinable does not detract from the comparison in the least for the true test of the Distinct Element method lies in its ability to produce accurate results along the lines $\psi = \phi$ and $h/b = \cot \psi$ which, as Figure 3.7 indicates, it has done.

## 3.4 Two Block Limiting Equilibrium Model

Goodman (1976) presents a method by which a Limit Equilibrium analysis of two interacting blocks can be performed with the aid of a stereonet. Figure 3.8 illustrates the general nature of the problem; a rock slide consists of two free blocks, one of which is in an active or loading state, the other is in a passive or resisting state. Sliding of the passive wedge is initiated by load transfer from the active wedge which, by definition cannot be sustained by friction alone along its base planes; moment equilibrium is not considered.

The procedure consists of three steps:

1. analyze active block with plane 3 as a free face: find $F_p$ required
2. analyze passive block with plane 3 as a free face, and with load - $F_p$
3. system is safe if resultant or passive block falls within the friction cone to the normal to plane 2

Note that if the angle that the resultant on plane 2 makes with the normal to plane 2 is taken as the friction angle on plane 2, then limiting equilibrium conditions exist throughout the mass.

Several different geometries were analyzed by this method for comparison with the Distinct Element method. Care was taken to ensure that the geometries chosen for analysis would fail with a minimal amount of rotation and with full frictional resistance developing on all planes in accordance with the basic theory. The results of several of the test cases are presented in Table 3.1,

some of the geometries and the associated stereographic projections are presented if Figure 3.8.

The difference in the friction coefficient for stability on Plane 2 as calculated by two block Limit Equilibrium as compared to that calculated by the Distinct Element method was found typically to be on the order of one percent.

| | Limit Equilibrium | | Distinct Element | | Relative Difference |
|---|---|---|---|---|---|
| Case | $\phi$ | $\mu$ | $\phi$ | $\mu$ | in $\mu$ |
| 1 | 23.0° | 0.425 | 23.3° | 0.430 | 1.2% |
| 2 | 25.5° | 0.477 | 25.7° | 0.482 | 1.0% |
| 3 | 30.6° | 0.591 | 30.8° | 0.597 | 1.0% |
| 4 | 33.0° | 0.649 | 33.1° | 0.652 | 0.5% |
| 5 | 37.6° | 0.770 | 37.5° | 0.767 | -0.4% |

Table 3.1 Comparison of the coefficient of friction required for stability as calculated by Limit Equilibrium and by the Distinct Element method.

Other geometries, in which rotation played a major part in the failure, were analyzed and compared by the two methods. A typical geometry investigated is illustrated in Figure 3.10. The friction coefficient calculated by two block Limit Equilibrium for this geometry was found to be 0.554; the friction coefficient calculated by the Distinct Element method was found to be 0.490. The resulting difference in the friction coefficient was thus eleven percent. If, however, a Limit Equilibrium analysis

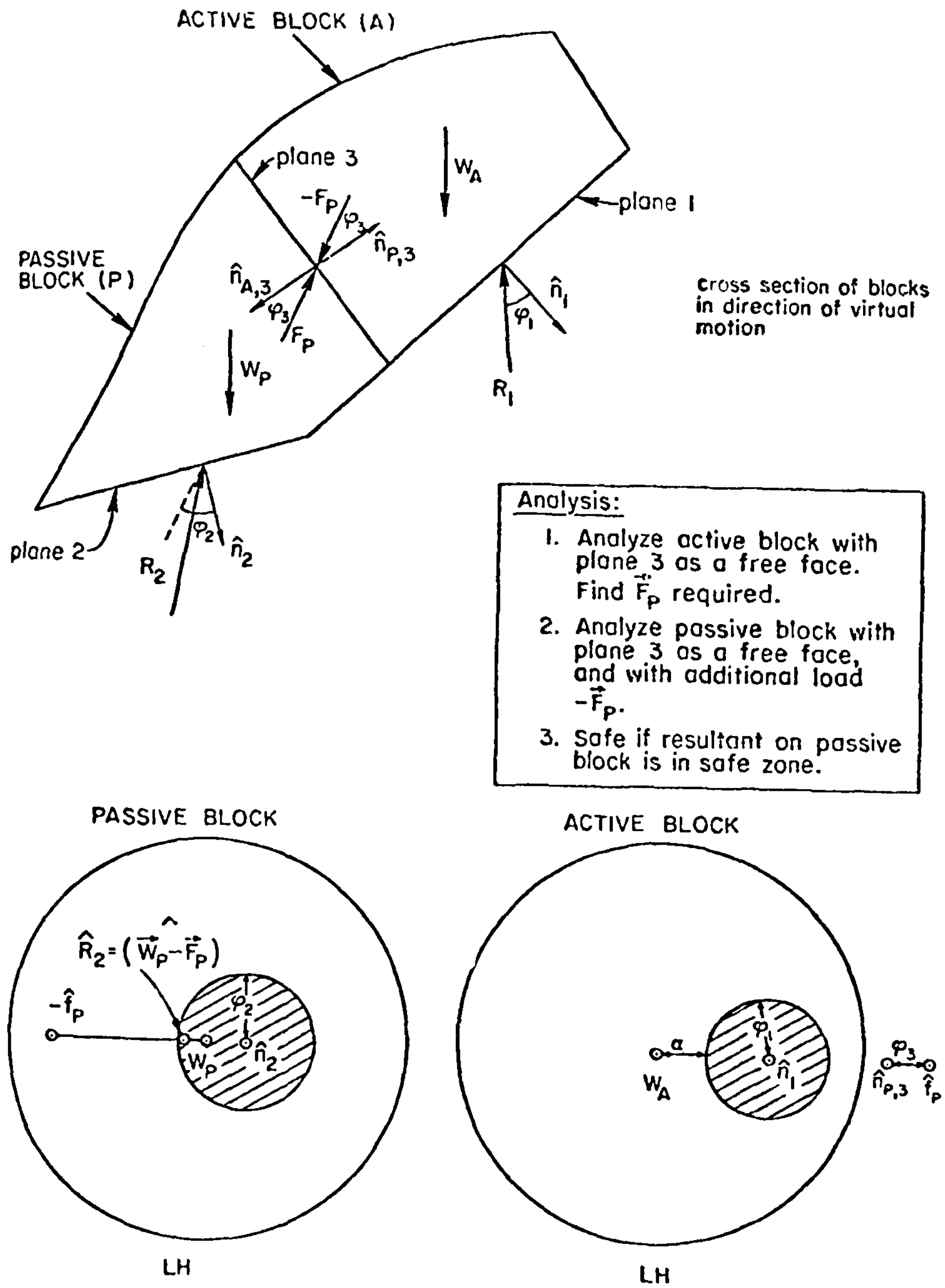



Figure 3.8 Parameters for two dimensional, two block Limit Equilibrium analysis (from Goodman, 1976)

incorporating rotation is performed, the friction coefficient for stability of the passive block is found to be 0.477 with a resulting difference in the friction coefficient of 2.7%. The geometry, stereographic solution and idealized force distribution are shown in Figure 3.10.

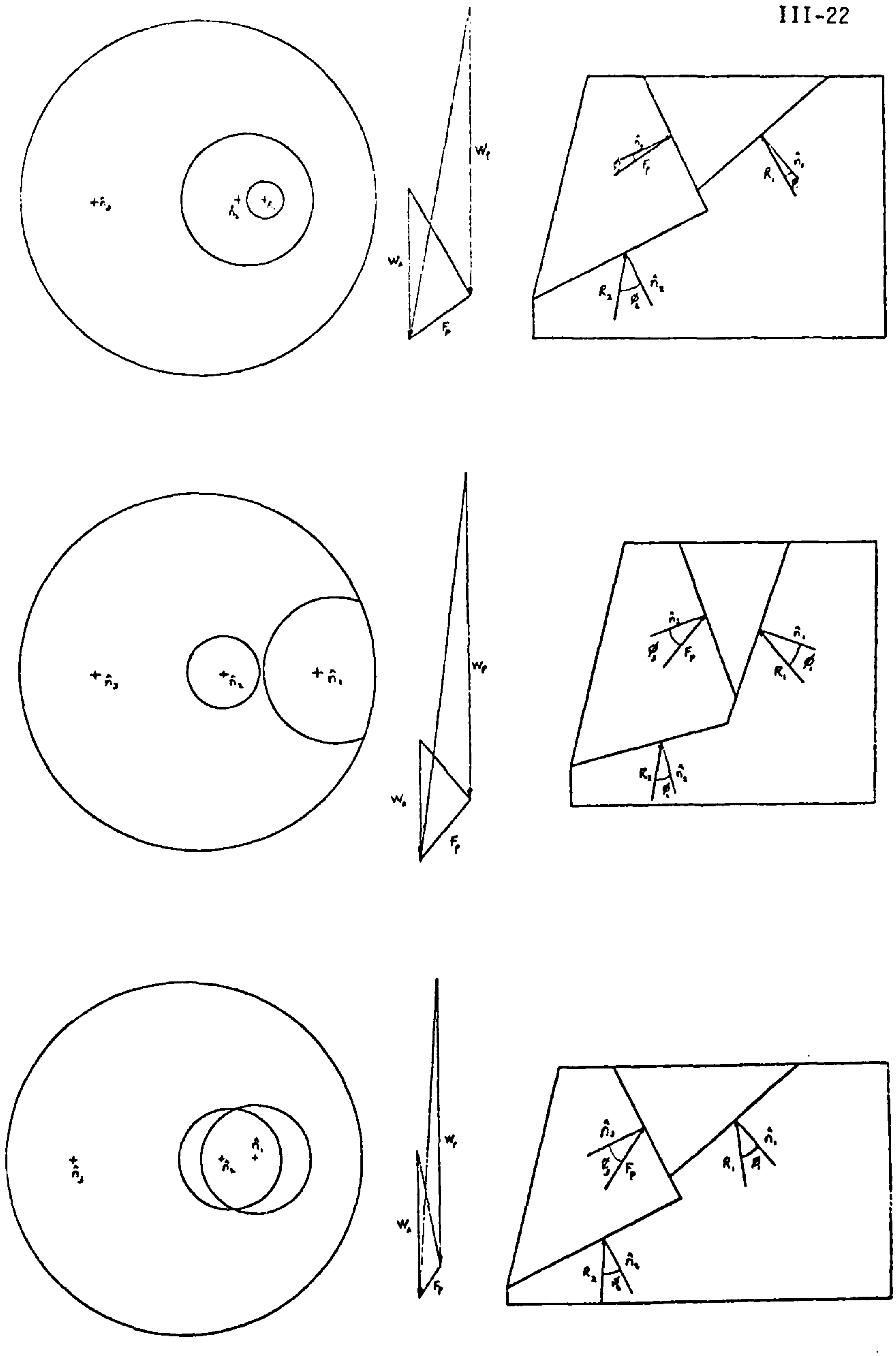
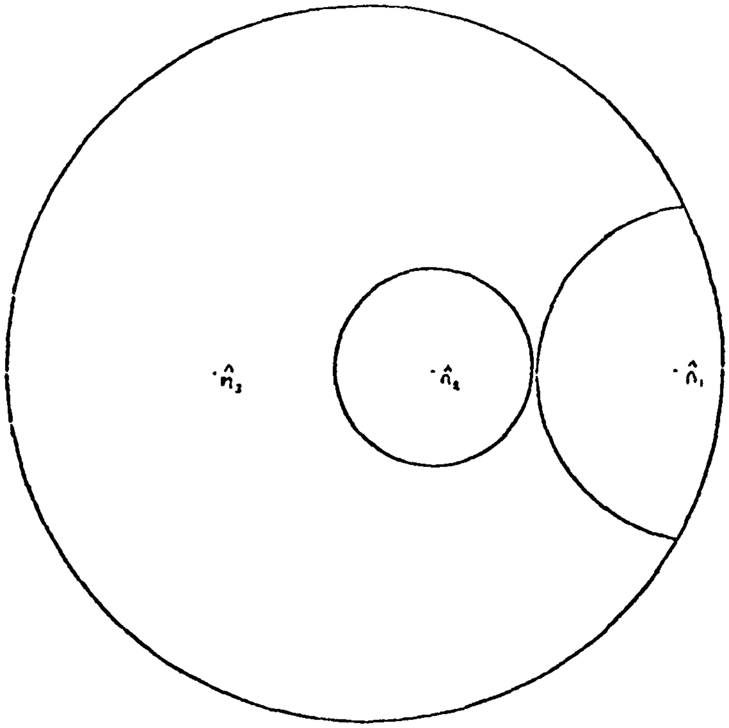
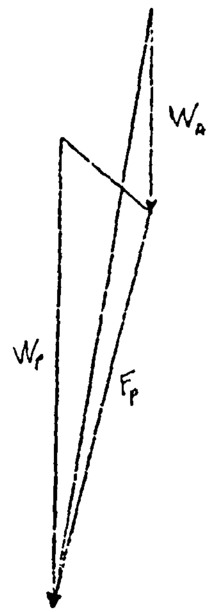


Figure 3.9 Geometries, force polygons and stereographic solutions for representative two block cases analyzed by Limit Equilibrium.




(a)

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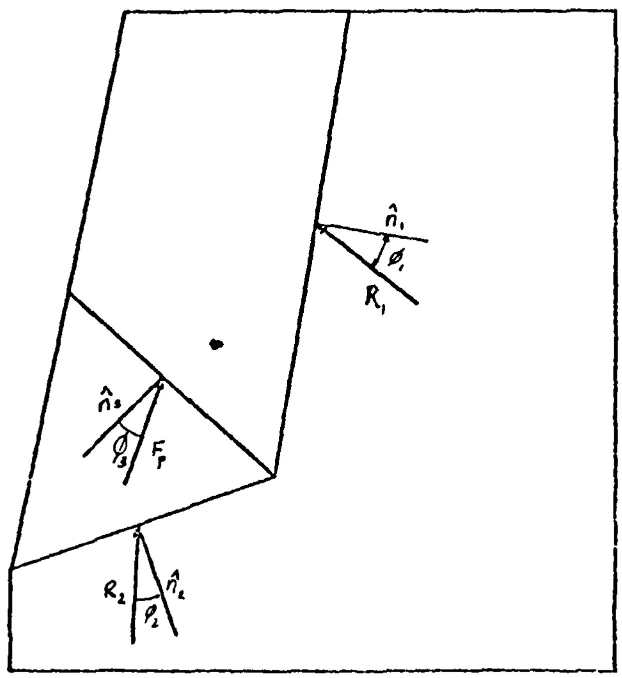


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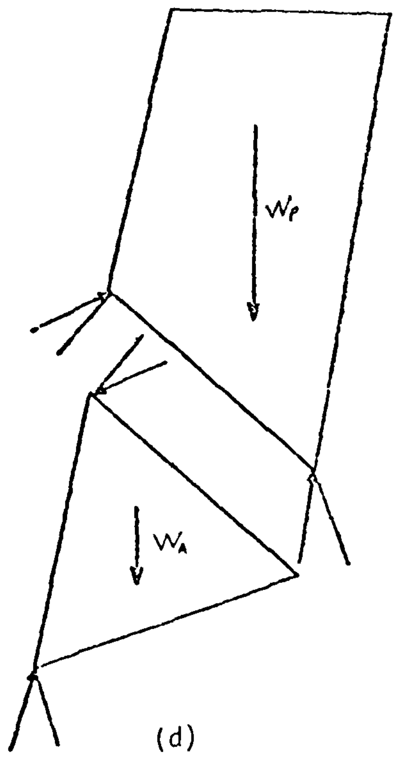



(d)

Figure 3.10 (a) (b) (c) Limit Equilibrium analysis of a two block model where toppling is an expected failure mode; (d) Alternative force distribution for consideration of moment equilibrium.

3.5 Embankment Stability Utilizing Equilibrium of Slices

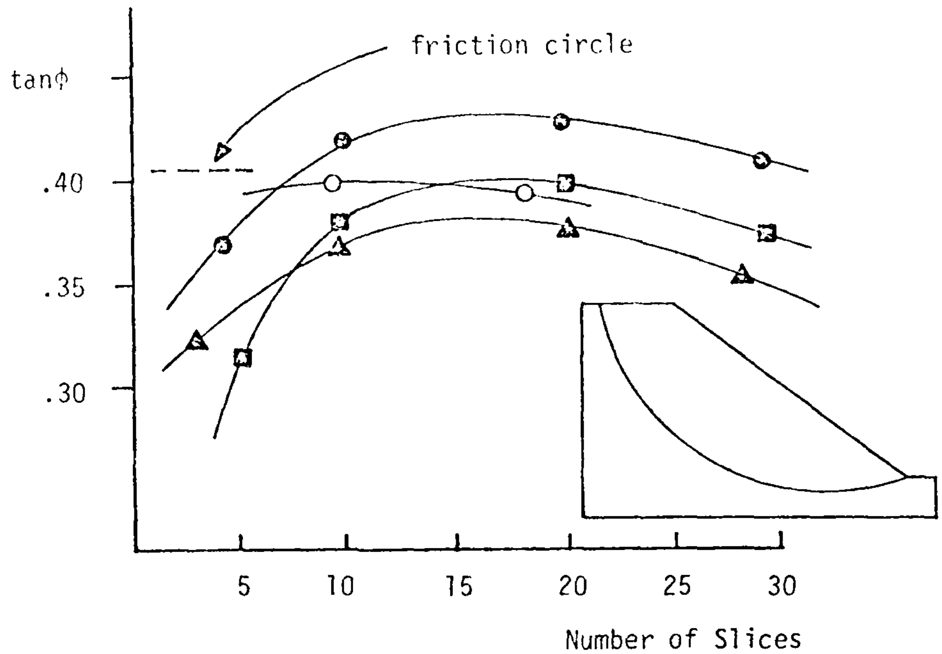
An interesting test of the ability of the Distinct Element method to calculate a comparable solution arises in a comparison to the method of slices approach commonly used to assess the stability of a soil slope. Although the intent of the method of slices approach is to model a soil slope as failing plastically at all points simultaneously, equilibrium is calculated for a number of vertical slices whose behavior can best be described as that of a rigid block. There are a number of approaches to the solution of this problem, but they all have in common the fact that an idealization is made in the true force distribution on a slice to make the solution statically determinate. Examples of idealizations which can be solved by hand calculations are the Fellenius and simplified Bishop techniques (Lambe and Whitman, 1969) which assume zero force resultant in the direction normal to the failure arc and zero force resultant in the vertical direction, respectively. More complex lateral force distribution schemes exist, and are typified by the method of Morganstern and Price (1965), which assumes the lateral force distribution parallels an originally unknown but determinable function, and the method of Spencer (1967, 1973), which assumes that the lateral forces are inclined at a constant and determinable yet originally unknown angle. The solution of these more complex schemes is typically highly iterative and best handled by a computer.

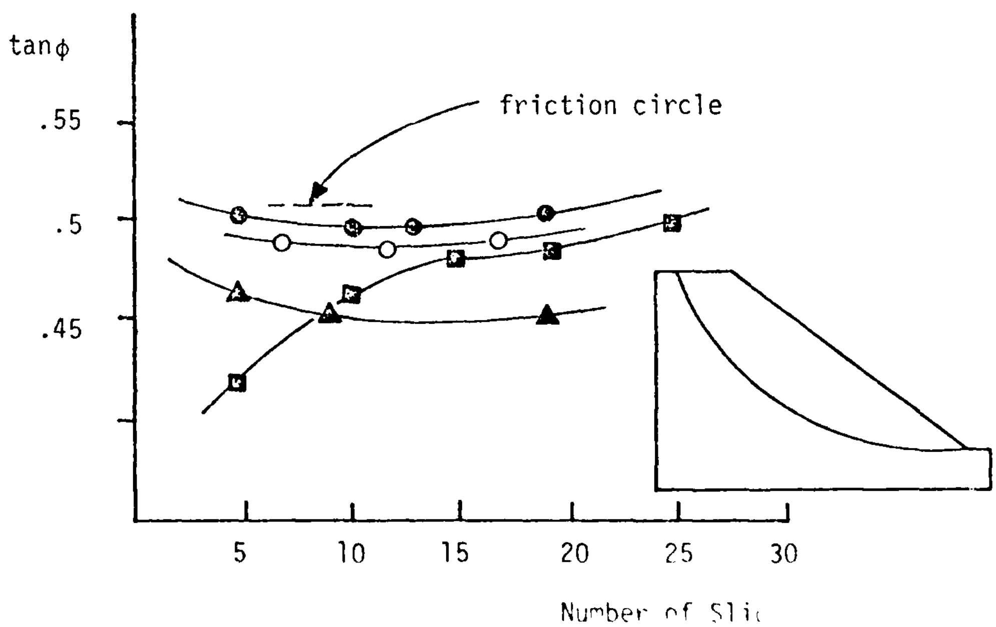
To keep a proper perspective it must be noted that Fellenius chose to ignore the side forces in his method since the error introduced was on the order of five percent and that Beichmann in

1937 used 13 different and reasonable assumptions about the side forces to demonstrate that the maximum difference among the methods was only four percent (Golder, 1972). In addition, Spencer (1967, 1973) was able to demonstrate the insensitivity of the moment equation to the slope of the interslice forces. The inclusion of a constant side force inclination led to a significant reduction in required computational time as there was no longer any need to calculate the thrust position function as in the method of Morganstern and Price.

For purposes of comparison to the Distinct Element method, four commonly encountered method-of-slices analysis were used. The friction circle technique, Taylor (1937), although not a slice type analysis, was also used. With the normal stress concentrated at a single point, this equilibrium solution establishes a lower bound safety factor for all method-of-slices solutions which satisfy statics. The Fellenius and simplified Bishop methods (Lambe and Whitman, 1969) were used because of their simplicity and tendency to bracket the other methods (Whitman and Moore, 1963). Wright's modification of Spencer's method (Major, et al., 1976) was chosen as representative of the methods that include lateral forces, primarily due to its superiority in computational speed.

The results of the comparisons for two slope configurations are presented in Figure 3.11; the significant difference between the cases is that case B is more nearly planar owing to the larger radius of the failure surface. Inspection of the figure illustrates several interesting points as outlined in the following




Fellenius

Simplified Bishop

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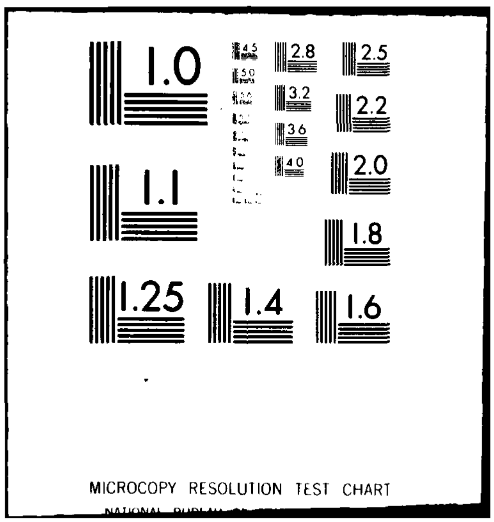
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MICROCOPY RESOLUTION TEST CHART

paragraph.

Firstly, the variation in the friction coefficient required for Limit Equilibrium conditions is a function of the number of slices; the fact that Spencer's method, which utilizes lateral forces, is less sensitive to this parameter probably indicates the reason for this. As the blocks get thinner, they become rotationally unstable and lateral forces are required to maintain equilibrium. On the other hand as the number of slices becomes smaller, the system begins to act as an active/passive block system and once again, lateral forces are required for equilibrium to be reached. In practice, it is recognized that these problems are avoided if the number of slices is in the range of from ten to twenty. Within this range the friction coefficient as calculated by the Distinct Element method is within two percent of the method incorporating side forces (Spencer-Wright) and typically within five to seven percent of that given by either Fellenius or Bishop. Secondly, the friction coefficient calculated by the Distinct Element method diverges from that calculated by the other methods for a small number of slices. This is probably due to the fact that the Distinct Element method approximates the circular failure arc by a series of straight line segments and the possibility that any given segment could have an unwarranted influence on the sliding behavior. A given line segment could lower the inclination of the failure surface at any point along the slope with a corresponding decrease in the resultant friction coefficient required for stability. In contrast to this is the case where the

failure arc is approximated by a larger number of slices; in this case the average slope of the failure arc is correctly represented. These two cases are illustrated in Figure 3.12.

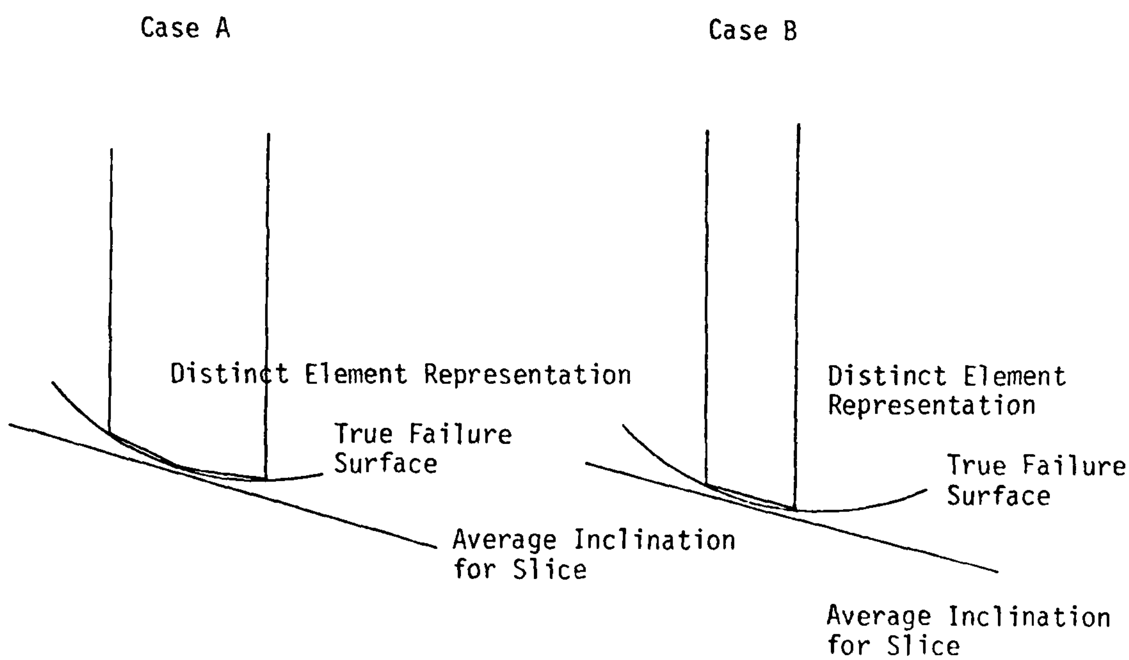


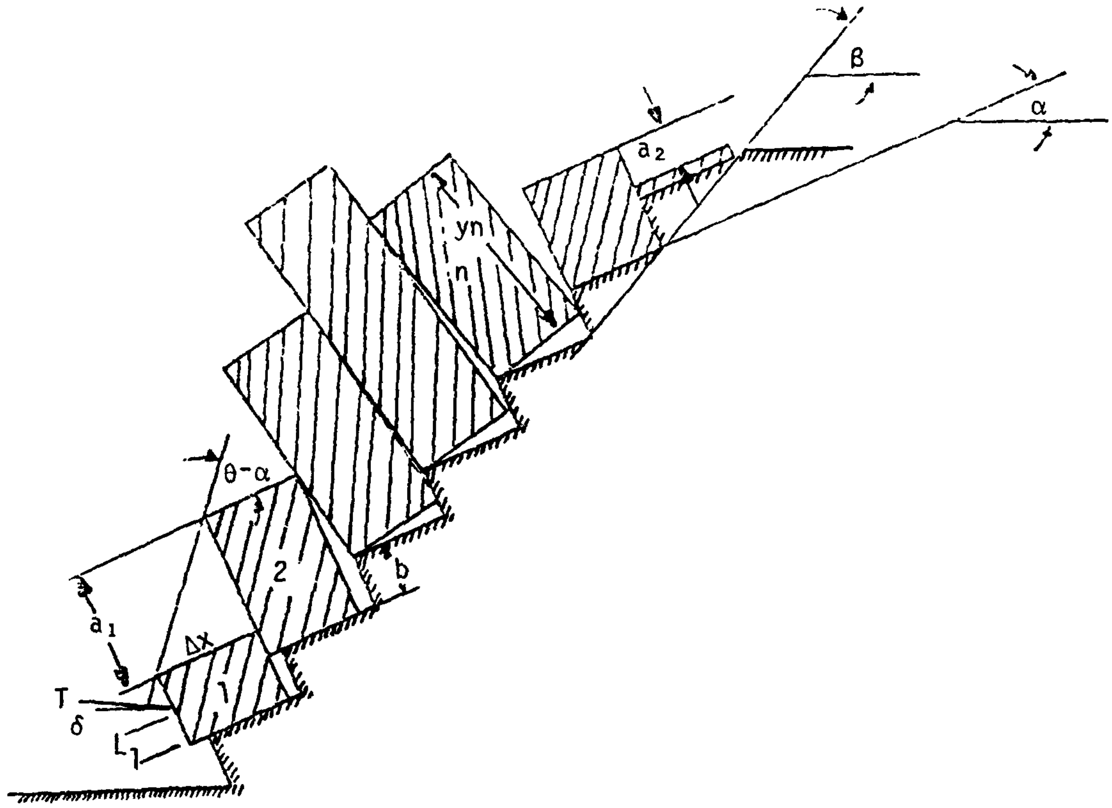

Figure 3.12 Possible mechanism (exagerated view) for divergence of Distinct Element method from slice methods as slice thickness increases. Note that in case A, sliding can occur on a line segment which has a higher inclination than the average for that section of the arc while this does not occur in case B.

3.6 Multi-Block Limiting Equilibrium with Toppling

Goodman and Bray (1976) demonstrated that block toppling can easily be analyzed by Limit Equilibrium methods for the special case of blocks resting on a positively stepped base as shown in Figure 3.13(a). Sliding and toppling modes of failure are analyzed for each block according to the failing configurations illustrated in Figure 3.13(b). The indeterminacy in the equilibrium equation for each block is resolved by assuming that full frictional resistance develops at each contact point. The other major assumption in the method is the position of the points of contact.

Beginning with the uppermost block, the force to prevent toppling and the force to prevent sliding are calculated. The larger of these two numbers dictates whether toppling or sliding will occur; however, if both forces are negative, the block is stable. For the analysis of the next block down the slope, the larger of the two forces (or zero if the block is stable) is applied to the downslope block and the stability of that block determined. The method continues down the slope until the toe block is reached. The force required to maintain equilibrium of the toe block is the cable force required to stabilize the entire slope since all excess driving forces have been transferred to the toe block by the calculation method. The method is general enough to handle any location and orientation of the cable force.

Two of the geometries chosen for analysis are illustrated in Figure 3.14; although similar in appearance, they differ in that the toe block will fail by sliding in one case and by toppling in the other case.



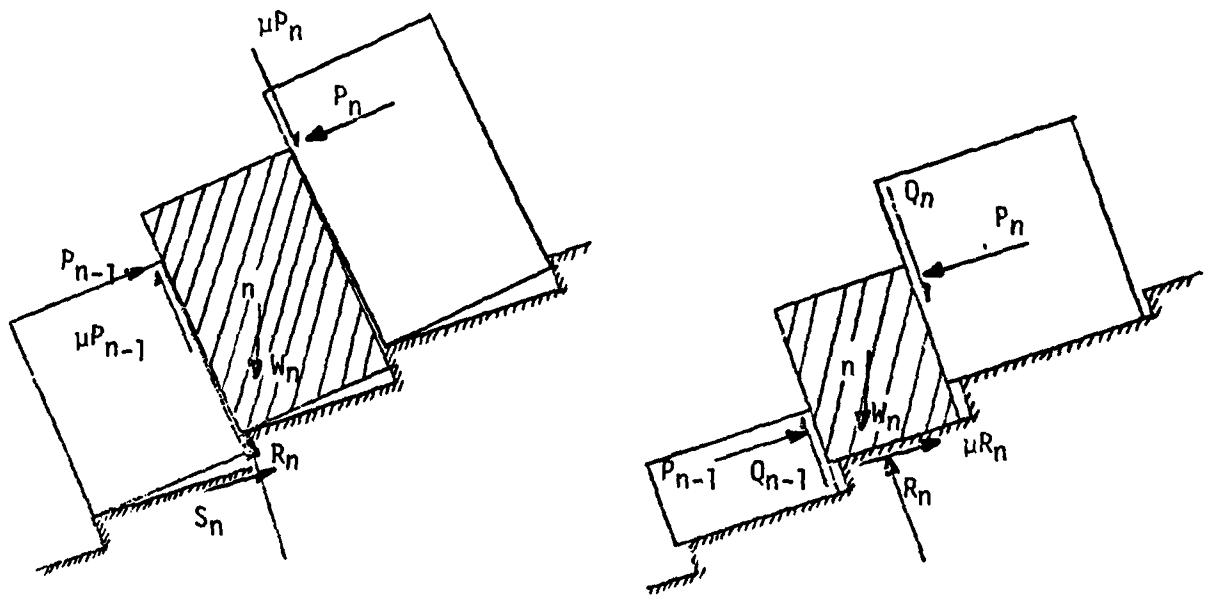




Figure 3.13 Conditions for toppling and for sliding of a given block under limiting conditions (after Goodman and Bray, 1976).

One additional point must be considered when the mode of failure is dominated by toppling. Whereas the stability of a system of sliding blocks may be analyzed with the Distinct Element method by beginning with a condition that is stable with respect to frictional sliding and reducing the friction coefficient until failure occurs, the situation that exists when toppling modes of failure are present is more complex. On the one hand, frictional resistance on the sides of the block and at the corner about which rotation is occurring cannot be fully developed unless rotation induced lateral movement has been allowed to occur between blocks. But on the other hand, once some rotation has occurred, the geometric configuration of the blocks is such that a higher force is required to maintain stability with respect to toppling.

In a comparison of the Distinct Element method and the Goodman and Bray Limit Equilibrium method, this fact must be taken into consideration. Since the significant coordinates are always available during the running of the Distinct Element program, the amount of rotation of an individual block can always be calculated at any time during the running of the program. In addition, a sensitivity analysis relating cable force to base plane inclination was performed using the Goodman and Bray Limit Equilibrium method.

The variation of the step inclination illustrated in the figure does not represent an actual change in the geometry of the model but reflects the actual displacement of the blocks due to rotational movements in the Distinct Element model. The value of the cable

force determined by the Distinct Element method for several values of block rotation is illustrated. The corresponding values as determined by Goodman and Bray's method are also plotted for equivalent rotations. By comparing the data in this manner, there is assurance that the difference in calculated values is not due to a failure to compare equivalent models.

The results of the two comparisons are presented in Figure 3.14; part A illustrates the case of the toe block toppling and part B illustrates the case of the toe block sliding. Inspection of Figure 3.14 shows that the response of the Distinct Element model is similar to that of the Goodman and Bray Limit Equilibrium model; the cable force calculated is also similar for both models.

The relative difference in the calculated cable forces is approximately ten percent for the case of toe block sliding and approximately twenty percent for the case involving toe block rotation. Examination of Figure 3.15 illustrates several discrepancies between the contact force distribution assumed by Goodman and Bray and that calculated by the Distinct Element model. These discrepancies all have a direct bearing on the magnitude of the required cable force and help to explain the difference in the value of the cable force as calculated by the two methods.

The contact forces indicated by the number 1 in the figure indicate "elastic" compression of the block system due to the applied bolt force and result in an increased value of the bolt force required for stability. The contact force indicated by the

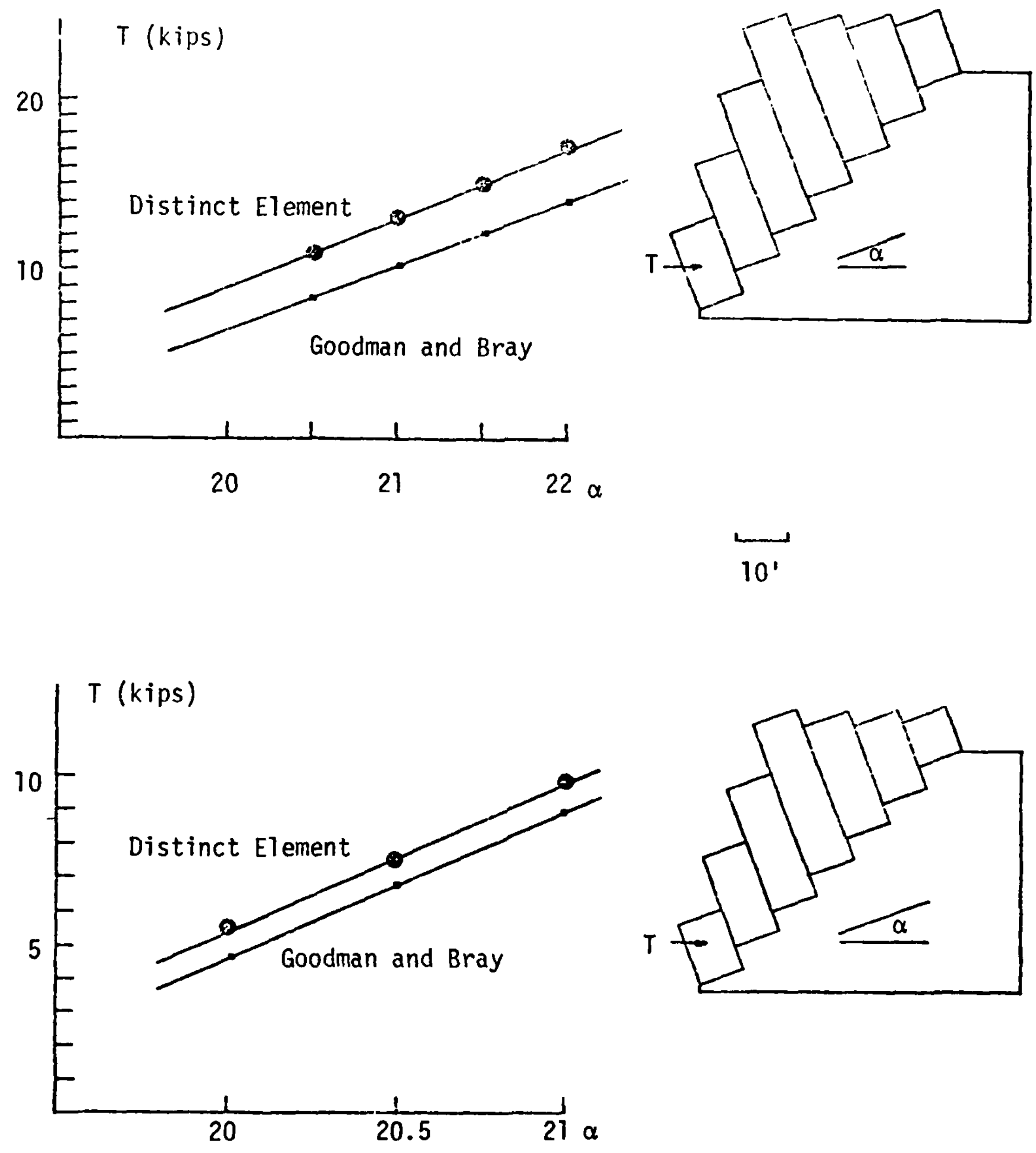



Figure 3.14 Comparison of Distinct Element calculated response of multi-block Limit Equilibrium and response as calculated by the method of Goodman and Bray (1976).

number 2 also reflects the tendency of the cable force to compact the system; as rotation begins, shearing resistance develops. This force however, acts to stabilize the block and thus, indirectly, reduce the required value of the cable force. The contact forces indicated by the number 3 directly contradict the basic assumption of Goodman and Bray - the development of full frictional resistance at all sliding contacts. Forces of this type acting at less than full frictional development increase the rotational moment on a block and thus increase the required value of the cable force.

In spite of these discrepancies, agreement of the models is still quite good indicating that the effect of the additional contact forces and the failure to mobilize full frictional resistance at all sliding contacts is slight. Additionally, rotational failure is very unstable and dynamic as opposed to simple frictional sliding which is essentially static. In light of this it is felt that the agreement between the Goodman and Bray model and the Distinct Element model is quite good.

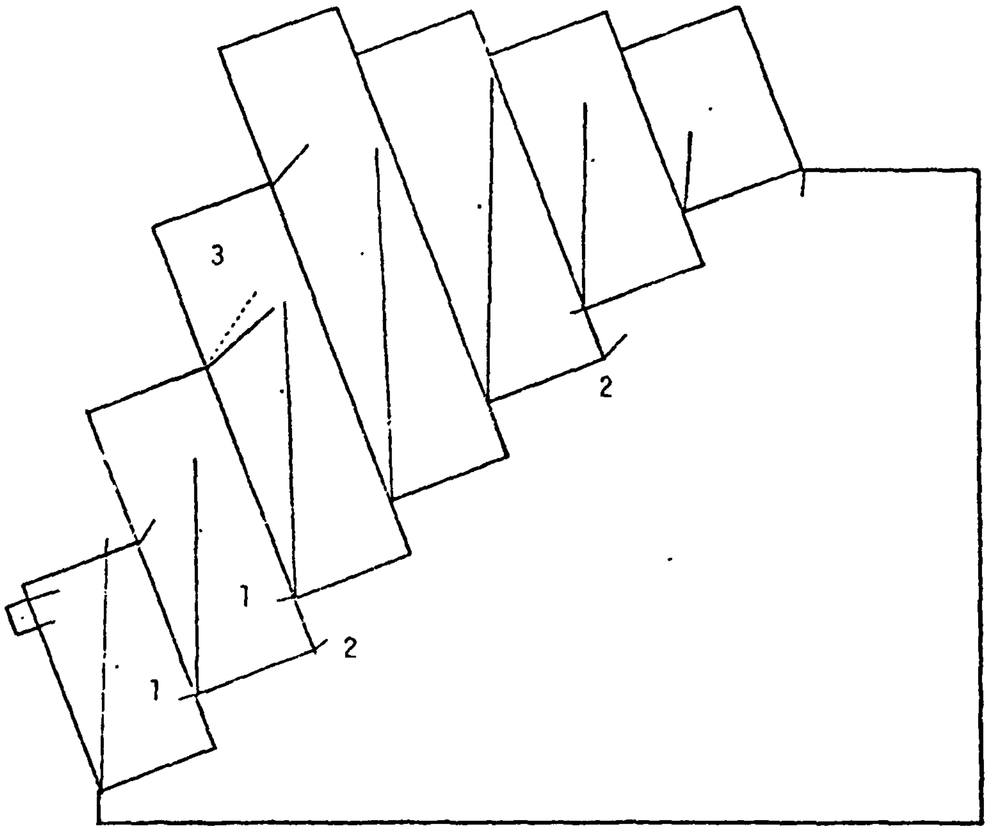
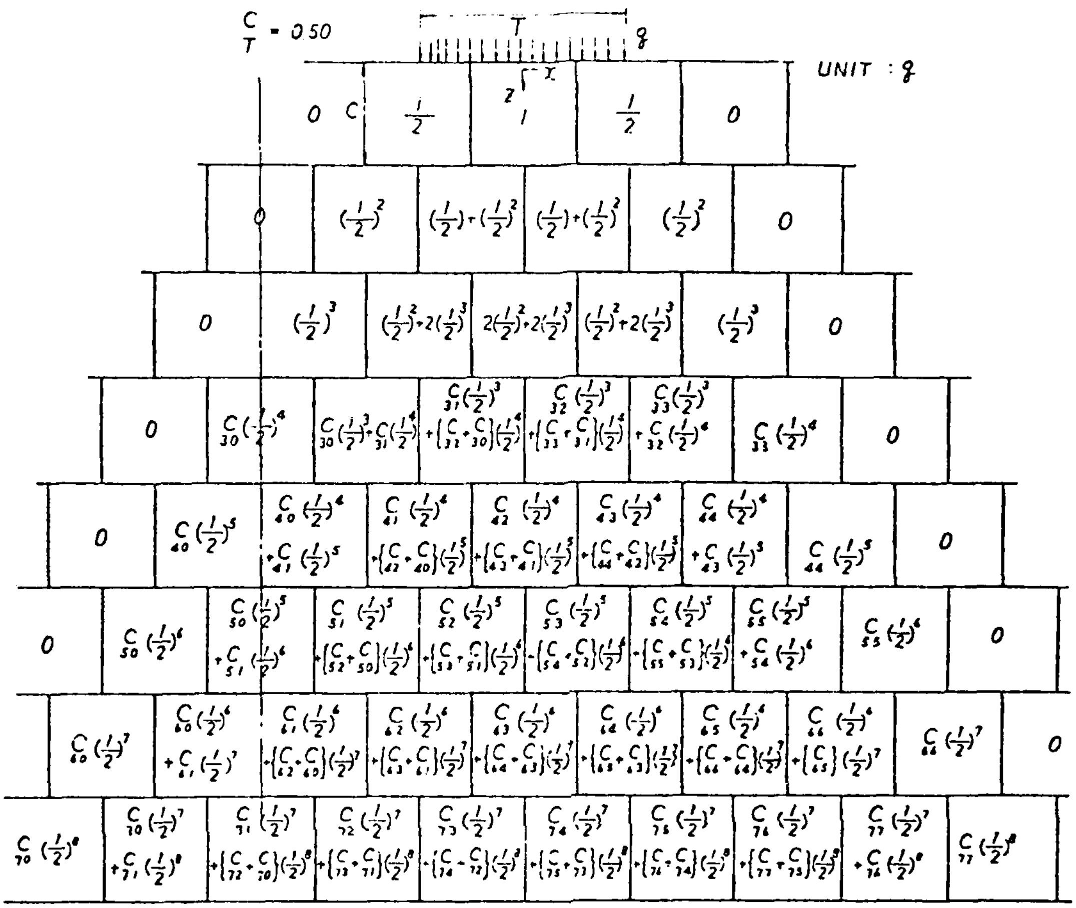



Figure 3.15 Observed discrepancies in the contact force distribution assumed by Goodman and Bray (1976).

## 3.7 Pressure Distribution in a Jointed Foundation

Several authors, notably Krsmanovic and Milic (1964), Trollope and Brown (1965), and Hayashi (1966) have investigated the distribution of pressure in a fissured or jointed mass loaded by a strip footing. Krsmanovic and Milic used physical, scale models incorporating pressure measuring transducers to examine behavior beneath the foundation, while Trollope and Brown and Hayashi deduced geometrically progressing load transfer factors that were used to predict the pressure distribution within the jointed mass. Of the three models, Hayashi's was used in a comparison with the Distinct Element method because the tests Krsmanovic and Milic performed were limited in scope and involved rupture of the blocks while Trollope and Brown's model relied upon the development of arching in the load transfer and was judged to be more applicable to the analysis of the behavior of a jointed mass on a settling foundation than to a strip loaded foundation (Trollope, 1968). Hayashi presents three approximations, each successively more complex in computational effort, to the distribution of pressures in a jointed, strip loaded foundation. The first approximation, which actually appears earlier in Froehlich (1933), approximates the jointed mass as a tiered assemblage of point loaded simple beams; the resultant pressure distribution for the case of no cohesion or frictional resistance reduces to the combined Pascal distribution as illustrated in Figure 3.16. The second approximation determines the elastic-plastic boundary below which slip no longer occurs by means of the




Note:

Vertical load acting on block is determined by combined Pascal distribution factor (indicated within block) miltiplied by one-half of total load acting on strip (0.5Tq)

Figure 3.16 Hayashi's first approximation to the vertical, normal stress distribution in a fissured foundation combined Pascal distribution.

Boussinesq equations and the third approximation attempts to correct for the conversion of strain energy to heat as slipping occurs. As the second and third approximations introduce additional simplifying assumptions concerning the material behavior, the first approximation was chosen for the comparison with the Distinct Element method.

One of the resulting comparison plots is illustrated in Figure 3.17. Even plotted to an exagerated scale, the similarity is obvious. The maximum discrepancy in the two methods, relative to the total load, is seen to be only four percent. The dissimilarity in the two methods arises in Hayashi's failure to include rotational terms in his analysis. Examining the first row of blocks beneath the strip load shown in Figure 3.16 suggests that the central block, owing to a larger load, will undergo a slightly larger deflection than will the blocks on either side. This will result in an inward rotation of the two side blocks and a corresponding increase of load in the region beneath the central blocks. Following this line of reasoning it is easy to see that had Hayashi considered rotations in his model, the resulting pressure distribution would have been, from a qualitative viewpoint, slightly higher in the central region and lower on the sides bringing it more in line with the pressure distribution calculated by the Distinct Element method.

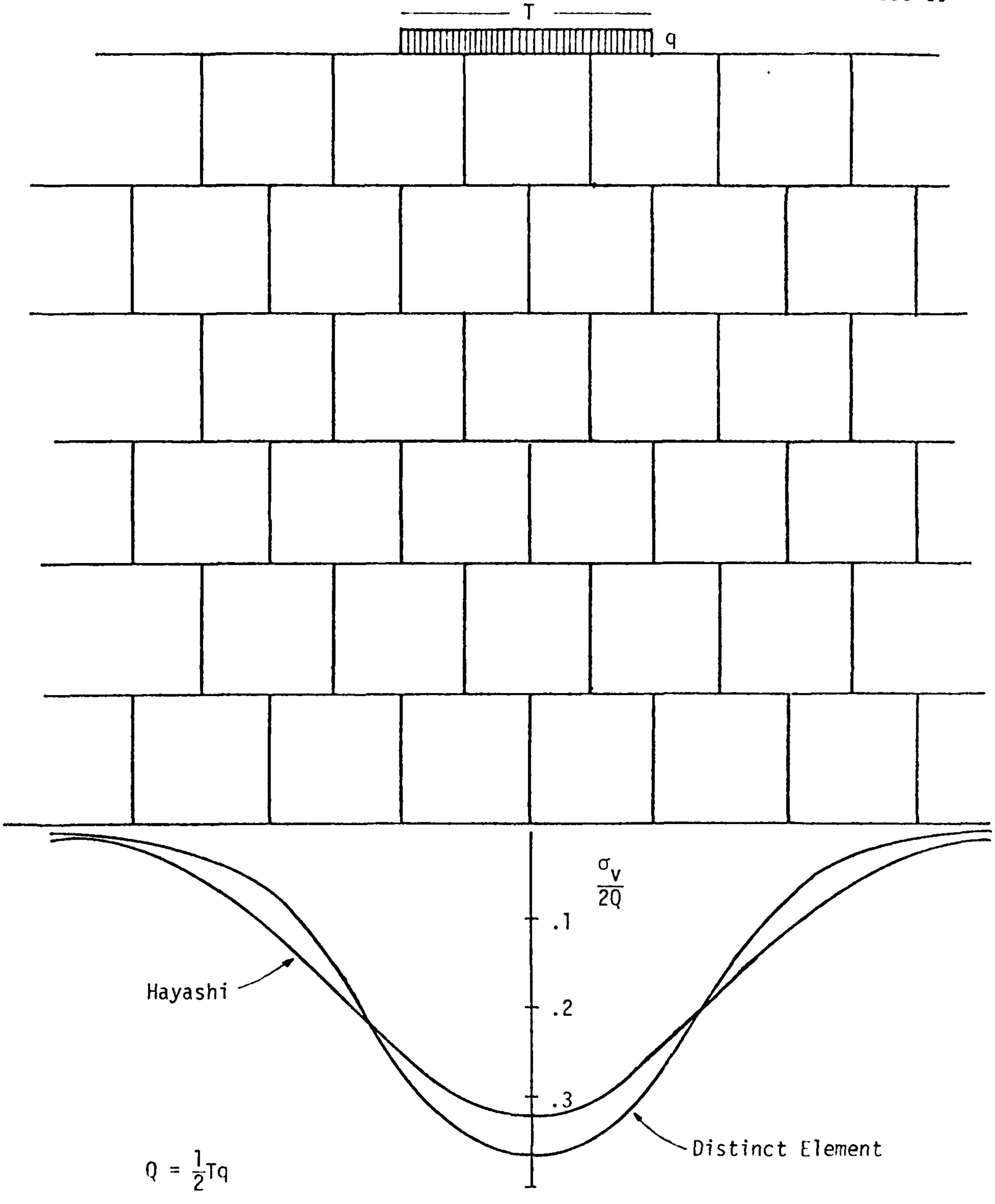



Figure 3.17 Vertical stress on a horizontal plane in a fissured foundation by the Distinct Element method and Hayashi's (1966) method.

## 3.8 Summary

It seems appropriate to conclude with a brief summary of the comparisons just presented, for the credibility of the remainder of this dissertation depends in part upon the acceptance of the validity of the Distinct Element method on the basis of the simple comparisons presented. Using a base shear apparatus, it was demonstrated qualitatively that the Distinct Element method calculated kinematically correct responses for several classes of complex problems where intuitive projections of the resultant mass deformational response were possible. For those Limit Equilibrium analyses of block models which represented essentially static situations, agreement was typically within one or two percent; even for the more dynamic situation involving multi-block rotations, agreement was on the order of ten percent. Finally, for that situation where it was possible to duplicate all of the assumptions regarding mass behavior, the Distinct Element method was observed to calculate a pressure distribution beneath a strip loaded foundation that was essentially similar to that calculated by Hayashi's (1966) theory.

Confidence in the method depends upon extending this credibility in the Distinct Element obtained solutions to problems where analytical solutions are not possible and where intuitive observations pertain to the mass deformational response are often not practical owing to the complex nature of the jointing.

There are no readily apparent reasons why extending the Distinct Element method to models which are more complicated

geometrically should result in answers that are any less acceptable than those generated for the preceeding comparisons. The Distinct Element formulation contains no underlying requirements to dictate where failure surfaces should develop nor does it require that the failure mode must somehow be reducible to idealized mechanisms of arching, toppling, or sliding. No mass elastic response equations with empirically modified parameters are incorporated in the model; no "joint elements" need be formulated. In fact, owing to the explicit nature of the formulation there is not even a need to form a stiffness matrix relating block deformations to inter-block loads.

The Distinct Element formulation is oriented toward the behavior of each block as an individual mass. The kinematic behavior of each block is independently calculated using Newton's law of motion; each block senses the blocks surrounding it only as boundary conditions. If the movement of a block leads to penetration or relative movement along the surface of another block then the normal and shear stiffness will lead to interblock contact forces by a simple application of Hooke's law with an upper limit to the forces set by the Mohr-Coulomb relation. These forces are simply treated as boundary conditions for the first block. When a contact is broken by a relative displacement between the two blocks involved, there is no longer a need to consider the effect that these blocks have upon each other.

In light of this single block orientation of the Distinct Element formulation there is no readily apparent reason why the only difference between a problem involving only a few blocks and

one involving tens or hundreds of blocks should be anything more than the extended time required to perform the calculations.

It should be noted, however, that the time step used in the calculation cycle is sensitive to the number of contact points a single block experiences at a given time. An increasing number of contact points can lead to numerical instabilities; this simply necessitates a reduction in the time step and is not an indication that the Distinct Element formulation is incapable of solving problems where single blocks simultaneously experience multiple contact points. In the present configuration, the equations are stable up to a maximum of eight points per block.

Additional verification comparisons of Distinct Element calculated responses are presented in the remaining chapters whenever it is possible to express quantitatively the behavior of the block jointed mass under consideration. The high degree of correlation exhibited by the comparisons presented in this chapter is also found to be true for the comparisons presented in the later chapters.

# CHAPTER IV

# THE STABILITY OF UNDERGROUND EXCAVATIONS IN JOINTED ROCK

## 4.1 Introduction

The first step in a rational support design method must logically be to predict whether or not a need for support actually exists. Rather than categorically stating that an excavation will or will not be stable if unsupported, it is more realistic to analyze a given situation by varying the values of the input parameters to determine those parameters to which the given excavation will be most sensitive. Using realistic values of the design parameters it can be determined if the excavation can be expected to stand unsupported or if support will be required. This type of investigation is typically found to be very sensitive to the input parameters, particularly those such as joint orientation and spacing, and the magnitude of the pre-existing stress field. Within the context of the expected variation of the parameters in the real situation it is then possible to make a qualitative statement about the stability of the excavation. This typically could be expressed in one of three ways: (1) within the expected variation of the input parameters the proposed excavation should be stable; (2) the expected variation in the input parameters indicates that the excavation may or may not be stable, suggesting a possible need for light supports; or (3), realistic variation of the input parameters indicates that the excavation will not stand unsupported, suggesting the need for heavier supports.

This chapter presents the results of numerous analyses of the

behavior of excavations in jointed rock in an attempt to determine which parameters had the greatest effect on the stability of the excavation. The models chosen for analyses are characterized by simple joint configurations and the behavior examined through the contact forces that exist between the blocks. This behavior is then interpreted in light of arching theory.

The term arch usually conveys the concept of a vaulted opening so that arching seems to describe the process by which the vaulted opening is formed. As used by Woodruff (1966), the term arching refers to the natural process by which a fractured material acquires a certain ability to support itself through the resolution of the vertical component of its weight into diagonal thrust. Arching theories examine the processes by which this stress transfer is accomplished.

Arching theories are based upon an analysis of beam behavior such as that presented by Woodruff (1966) which is illustrated in Figure 4.1(a). The analysis indicates that zones of tension and compression exist in the strata above the opening. In recognition of the fact that rock is relatively weak in tension, the lower row of the strata above the excavation is represented as being comprised of two independent blocks. The compressive forces which act to maintain the stability of the two blocks above the excavation are illustrated in Figure 4.1(b). The similarity of this force distribution to that of a three hinged structural arch is obvious; an analysis of excavation roofs in this manner is often termed linear arch analysis. As noted in Figure 4.1(b) no vertical force transmittal to the two roof blocks is assumed to occur. Thus

linear arch analysis, in this simple form at least, is an analysis of the lower row of strata only.

A significant portion of the results of this chapter are based upon the recognition of arching patterns in the Distinct Element calculated contact force distributions in the jointed rock surrounding an excavation. It is worthwhile then to briefly describe the origin of the contact forces and the manner in which the arches are recognized.

The contact forces represent the interaction between the blocks. A simple illustration is presented in Figure 4.1(c) where one block is shown on top of another; it is the upper block that is of interest. The weight of the block, shown as w in the figure is the force tending to cause movement. The interaction with the lower block leads to two contact forces which equilibrate the upper block weight. The contact forces are calculated from the overlap or interpenetration of the blocks as described in Chapter 2.8 and represent an equilibrium condition. The contact forces in more complex models are calculated exactly the same way.

The recognition of arching in the contact force distributions is based upon two observations. First, the arching phenomenon is indicated by the presence of relatively high magnitude contact forces. Arching involves diagonal thrust, but the vertical component of this thrust must be at least equal to the weight of the blocks being supported by the arch action. Since the arch thrusts typically form at low angles, the horizontal component of the thrust is usually large. The recognition of arching also is based upon the necessary

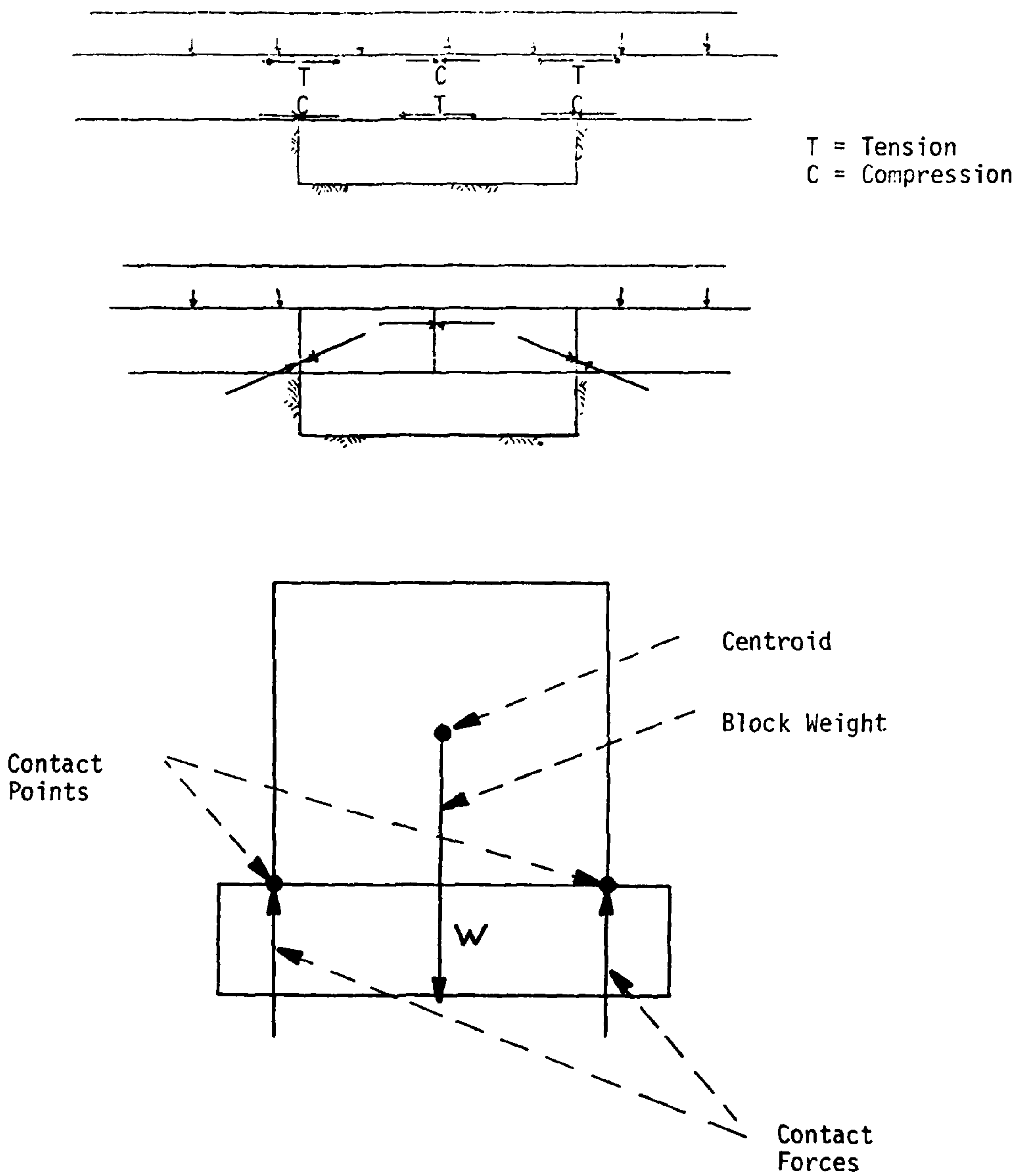



Figure 4.1 (a) General distribution of stress in a beam over an opening; (b) self supporting linear arch model; and (c) contact forces due to weight of block.

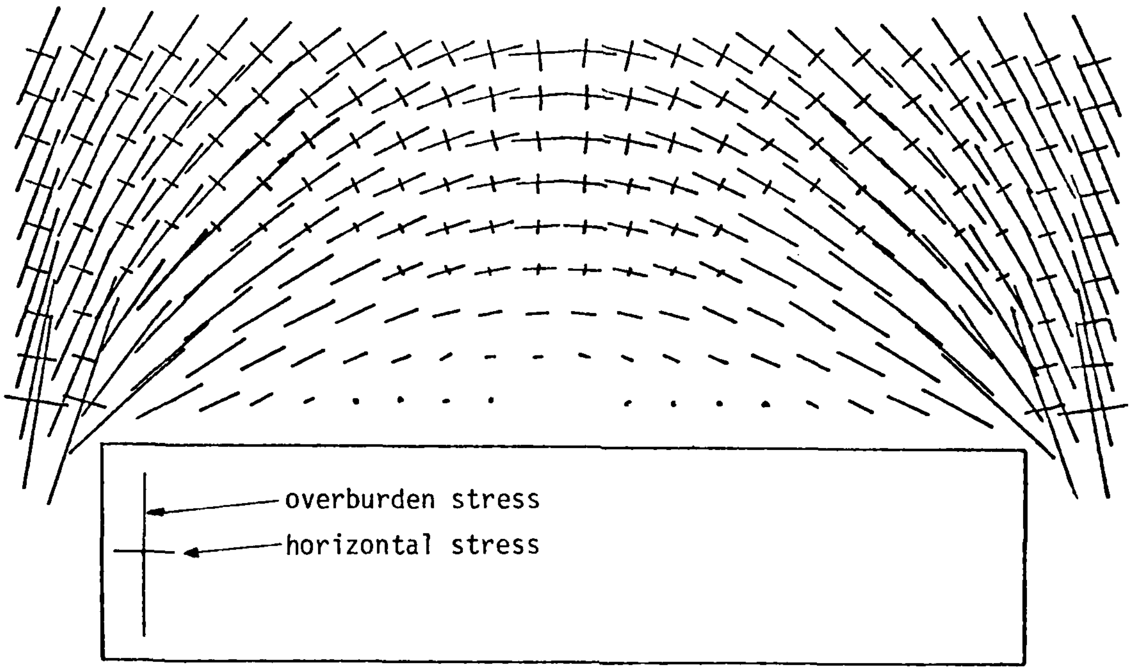
continuity of the force distributions. In particular, a block which is in equilibrium can have no unbalanced forces acting on it. Thus, the occurance of high contact forces in a region of low contact forces can only be possible if some mechanism is acting to transfer these forces to a high stressed region.

The analyses presented in this chapter indicate interactions exist within the mass which are typically neglected by arching theory. The analyses also indicate trends suggesting which input parameters have the most effect on the stability of an excavation in jointed rock.

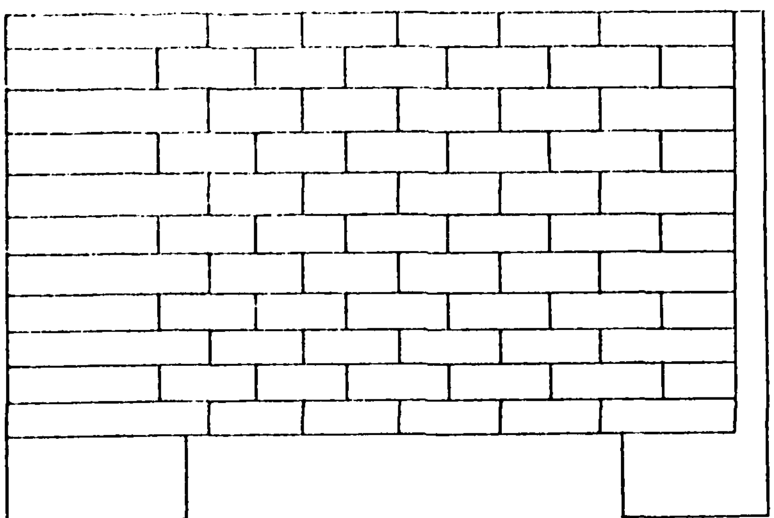
## 4.2 General Observations on Force Distribution Around Excavations in Jointed Rock

An elastic analysis of the behavior of the rock surrounding an excavation invariably leads to the conclusion that the vertical stress component is transferred to the rock on either side of the excavation resulting in a region of relatively low stress immediately above the excavation. This fact has been demonstrated many times in the past by using photo elastic models and recently by using Finite Element analysis. A typical plot of stresses surrounding an opening in an elastic medium is presented in Figure 4.2(a). Note that a zone of tension exists at the crown.

The Distinct Element method can be used to study the redistribution of stress due to an excavation in a jointed medium. As an example, consider the model of the roof of an excavation presented in Figure 4.2(b). Owing to the discontinuous nature of the vertical jointing, only blocks in the lower four rows are able, from a kinematic standpoint, to move into the excavation. The weights of all of the blocks, drawn to a common scale, are illustrated in Figure 4.2(c). All of the contact vector distributions for the jointed models illustrated in Figure 4.2 utilize the same force scale. Figure 4.2(d) illustrates the redistribution of forces that occurs as the room is excavated. Analogous to the elastic model, the bulk of the stress is transferred to the material on either side of the excavation and a destressed, triangular zone is seen directly above the opening. The lower portion of the

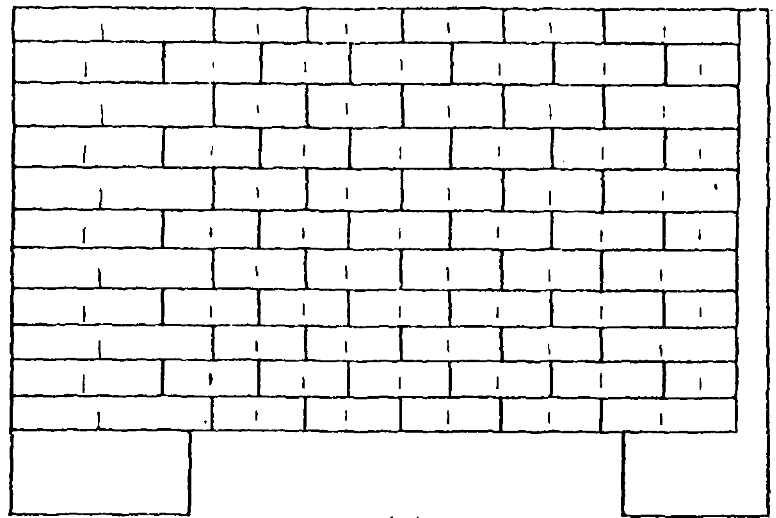



(a)

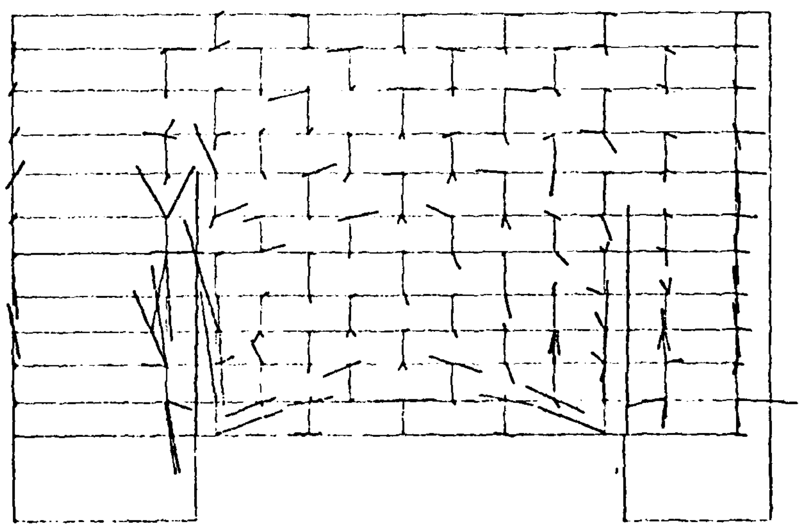


(b)

Figure 4.2 (a) stress distribution in roof of opening in elastic medium; (b) model for behavior of jointed roof.

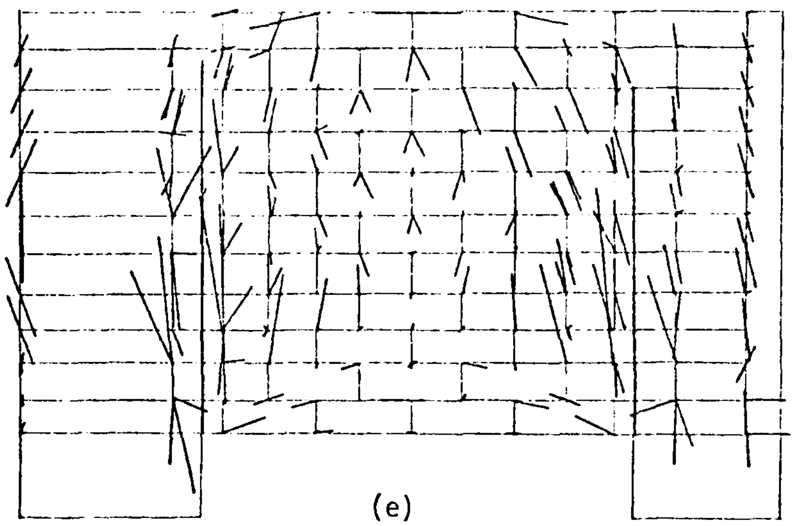


(c)

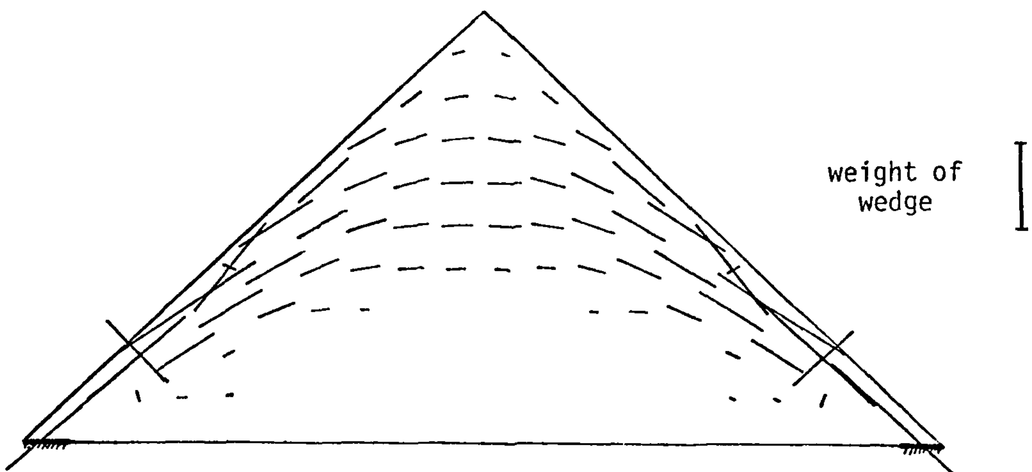


(d)

Figure 4.2 (continued): (c) block weights for jointed roof model; (d) force distribution in roof following excavation (overburden due solely to block weight).

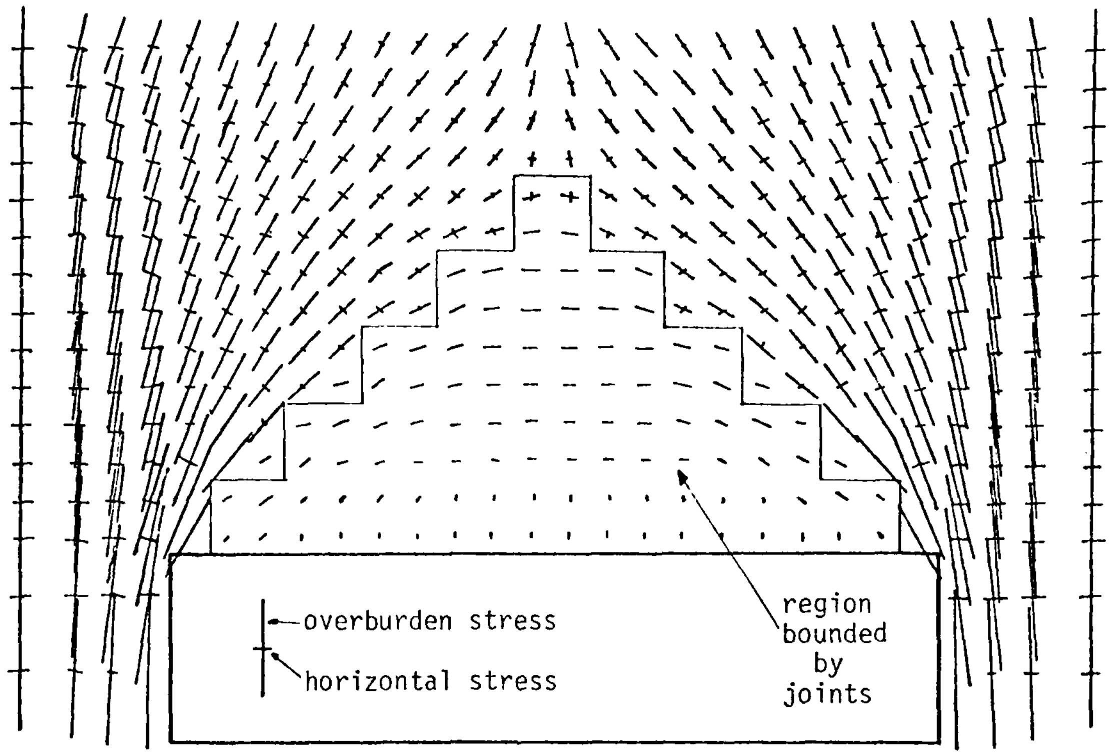


(e)




(f)

Figure 4.2 (continued: (e) force distribution in roof due to block weight and additional load to simulate greater depth: (f) stress distribution in triangular wedge supported at lower corners.




(g)

Figure 4.2 (continued): (g) stress distribution in jointed roof by Finite Element analysis.

triangular zone is seen to be in tension in the elastic case, whereas in the jointed model the absence of contact forces at the center of the bottom row of blocks indicates that the response of the jointed model is characterized by opening of joints. Furthermore, the pattern of compressional contact forces in the lower portion of the traingular zone indicates that an arch is forming and supporting the weight of the blocks within the triangular zone. The formation of this arch is discussed in section 4.3.3.

To investigate the effects of greater depth of the excavation, a uniform force was applied to the upper row of blocks in the model. Figure 4.2(e) is a plot of the stress distribution for the case where the applied forces correspond to a depth of excavation approximately ten times that illustrated in Figure 4.2(b). The same relaxed triangular zone characteristic of the low stress problem can be seen in Figure 4.2(e).

Comparison of the force distributions in the jointed models with that for the elastic case indicates that although arches are developing in both cases the support afforded by the formation of the arch is fundamentally different in the two cases. In the elastic case a single arch forms relatively high in the roof and the weight of the material in the destressed zone is supported through the development of tensional forces. The jointed models on the other hand develop two arches, one relatively high in the roof which delineates the destressed zone; and one that acts to support the lower strata.

This observation indicates a significant difference between the behavior predicted by elastic analyses and by the Distinct Element method. To determine to what extent the elastic behavior depended upon the continuity of the mass, several idealized models of roof behavior were analyzed, two of which are described here.

Figure 4.2(f) presents the results of a typical elastic analysis wherein the destressed zone was analyzed independently of the surrounding rock mass. The arch is still seen to form in the upper portion of the wedge of material and the material in the lower part of the wedge is in tension. This is in direct contrast to the behavior of the jointed masses analyzed by the Distinct Element method.

Figure 4.2(g) presents the results of a Finite Element analysis where the destressed zone was bounded approximately by a series of joint elements. Once again, the resultant behavior is characterized by a high arch and tensional forces; no evidence of arching action in the lower portion of the destressed zone is seen.

The behavior of the roof above an excavation in an elastic medium is thus seen to be fundamentally different than the behavior of a similar excavation in a jointed medium. The next portion of this chapter presents the results of an investigation to determine the causes of this fundamental difference.

## 4.3 A Model for the Behavior of Jointed Mine Roofs

The analyses discussed in this chapter deal with the behavior of the roofs of excavations in a medium where jointing is vertical and horizontal. The models have been kept simple deliberately so as to gain insight into relationships among the various parameters. As the overall goal of this study is to demonstrate the usefulness of the Distinct Element method in the analysis of excavation in jointed rock, more effort has been expended on demonstrating the effect of varying the significant parameters than on developing a single, all encompassing equation purported to describe the behavior of mine roofs.

The majority of the analyses to be discussed utilize similar jointed models, but although the chosen models are realistic the limitations were not imposed by the Distinct Element method as such; the techniques presented in this chapter are equally applicable to any model configuration. Although outside the scope of this study it is easy to envision an eventual compendium of various model geometries that portrays graphically the differences in the behavior of models.

### 4.3.1 The basic model

The basic model used for analysis consists of a rectangular opening in a rock mass with continuous horizontal jointing and discontinuous jointing in the vertical direction as shown in Figure 4.3. This model does not consider the effect of joint inclination but does allow for variation of the span, aspect ratio of the blocks and friction angle of the joint surfaces.

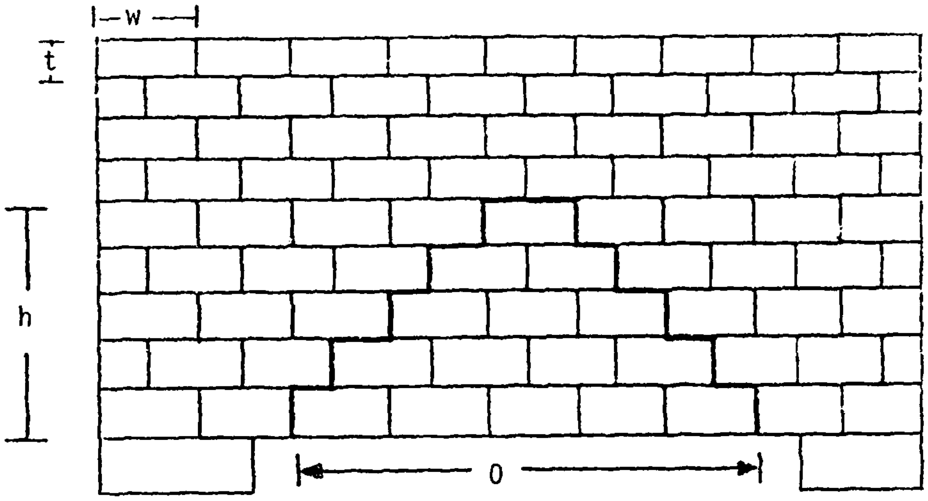



Figure 4.3 Jointed model upon which analysis was based. (0 is span width, w is block width, t is block thickness and h is height of the triangular wedge.

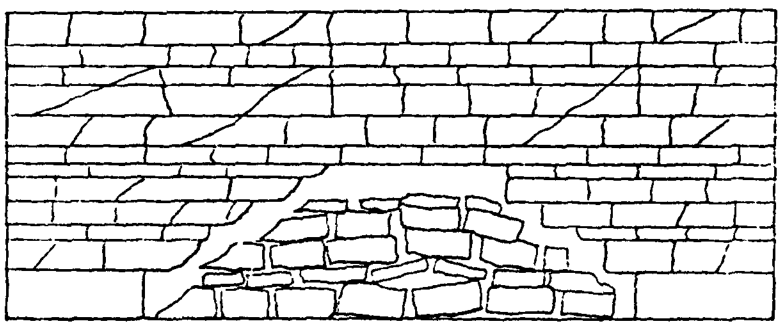


Figure 4.4 Diagramatic section of a roof fall (After Jones and Davies, 1929).

As justification for the use of the model a brief summary is given of four previous studies comprising theoretical calculations, laboratory as well as field observations and measurements, which utilized a similar model or support the model.

1) Behavior of Coal Mine Roofs

Jones and Davies (1929) presented a summary of their observations of roof behavior in British coal mines. They found that roof falls were invariably limited in height, the majority of the falls extending from 3 to 10 feet upward; falls exceeding 15 feet in height were considered exceptional. Judging from their description of the mining methods, the drifts were from 12 to 18 feet wide. They also concluded that the canopy of the fall was typically stepped along the sides "in the manner of a stairway viewed from below". A diagramatic section from their paper is reproduced in Figure 4.4.

2) Loads on Tunnel Supports

On the basis of observations and measurements of timber crushing in railway tunnels, Terzaghi (1946) proposed a classification scheme for the estimation of the maximum probable load on tunnel supports. Figure 4.5 presents one of the models used by Terzaghi to illustrate his concept that in relatively thin strata with many joints a peaked roof will develop. According to Terzaghi a constant load with a height equal to the height of the peaked roof acts to load the tunnel supports.

3) Laboratory Investigation of Arching

Trollope (1966) utilized a physical model with continuous joints parallel to the roof and discontinuous jointing in the

perpendicular direction to demonstrate the behavior of an excavation roof. Like Terzaghi he concluded that in general, two zones may be identified within the immediate roof.

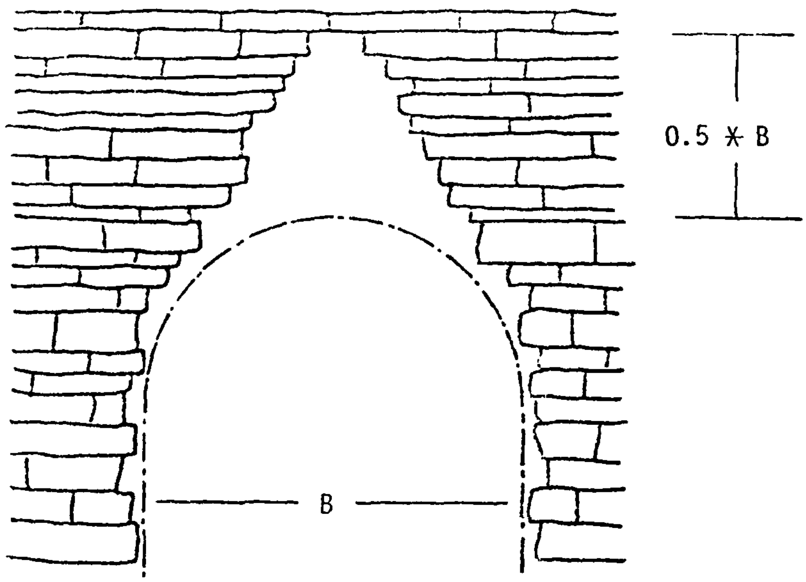



Figure 4.5 Maximum probable overbreak if no support furnished (Terzaghi, 1946)

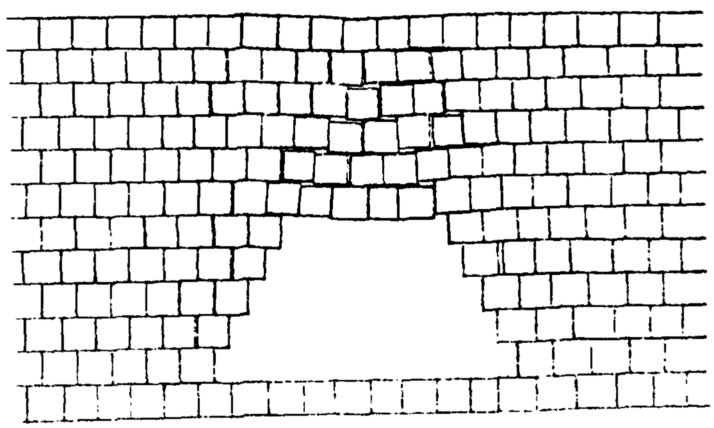


Figure 4.6 Trollope's Block Jointed Model (Trollope, 1966)

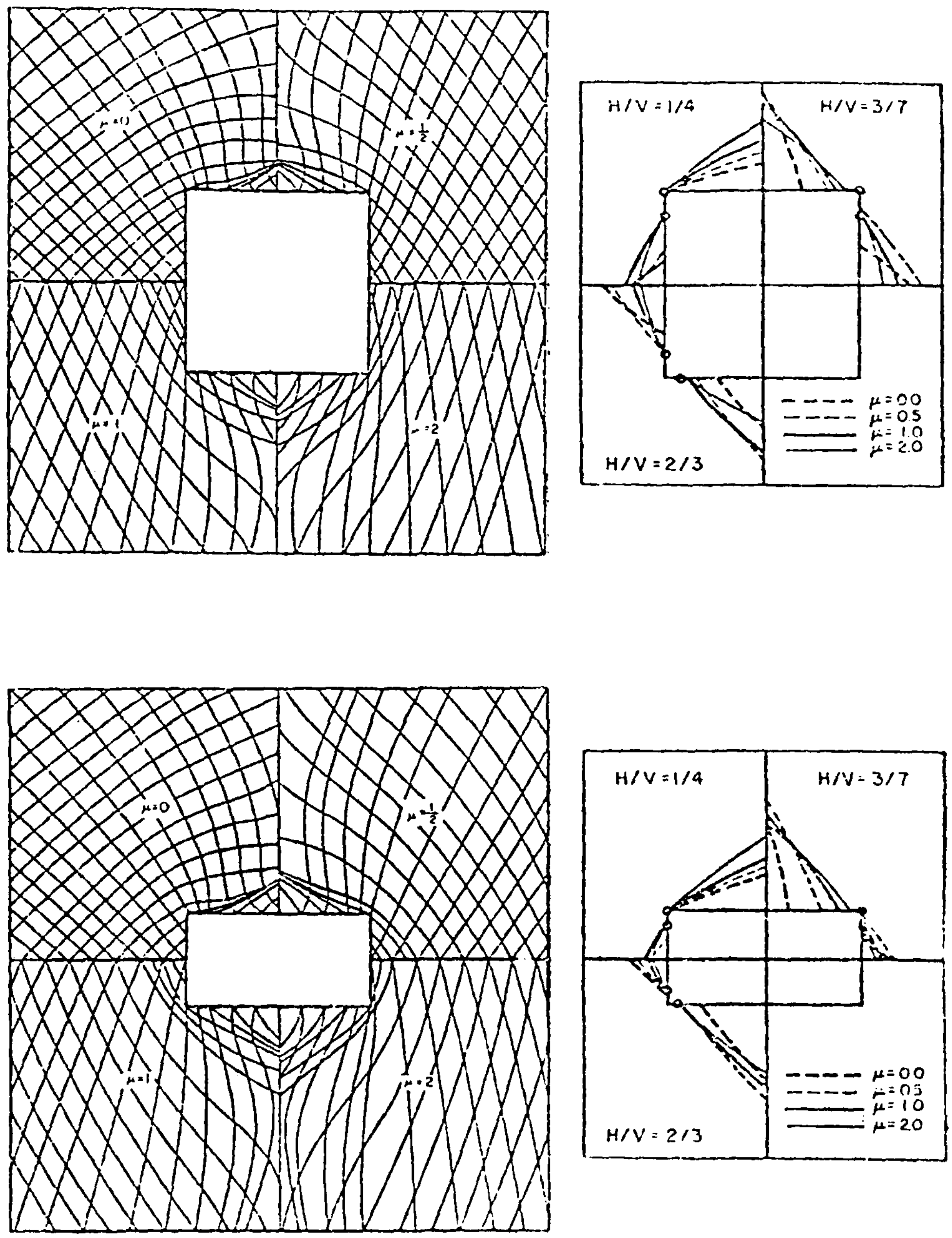
The first is inherently stable; the other zone which he referred to as the suspended zone, corresponds roughly with Terzaghi's triangular zone. Whereas Terzaghi concluded that the material within the zone would load the tunnel supports, Trollope was more concerned with the development of arching and stability within the suspended zone. Trollope's model is shown diagramatically in Figure 4.6.

4) Theoretical Stability Analysis of Underground Openings

Wang, Panek and Sun (1971) utilized Finite Element analysis techniques to determine the stress distribution surrounding excavations in a homogeneous medium. The maximum shearing stresses so calculated were then utilized in a Limit Equilibrium analysis to determine potential fracture surfaces. If the potential fracture surfaces were found to be unstable, they were termed critical. Although not directly applicable to problems of jointed rock, their results nevertheless indicate that the critical fracture surfaces define triangular wedges above the excavation. Possible and critical fracture surfaces calculated by their method for square and rectangular openings are illustrated in Figure 4.7. These plots indicate an expected maximum height of the triangular wedge of from 0.15 to 0.5 times the excavation width depending upon Poisson's ratio and the coefficient of internal friction.

### 4.3.2 Properties of the basic model

Referring once again to Figure 4.3 it can be seen that, by kinematic considerations, a triangular wedge of material is free to




H/V = ratio of horizontal to vertical stress
μ = coefficient of internal friction

Figure 4.7 Possible and critical fracture surfaces for square and rectangular openings. (Wang, Panek and Sun, 1971)

move into the excavation. The height of this triangular wedge (referred to by Terzaghi as overbreak and by Trollope as the height of the suspended zone) is easily calculated in terms of the excavation span and the thickness and width of the blocks defined by the jointing pattern.

The number of blocks (b) in the bottom row of the roof strata is given by:

$b = O/w$

O is the true span of the excavation

w is the block width

(Note that span is defined as illustrated in Figure 4.3)

Restricting the analyses to the case where all blocks are identical, it is easily verified that the height of the triangular wedge is given by:

$$h = b \cdot t \qquad 4.1$$

where: t is the block thickness

In terms of the aspect ratio of the blocks ($A = t/w$)

$$h = O \cdot A \qquad 4.2$$

Equation 4.2 is plotted in Figure 4.8 as a family of curves representing the wedge height as a function of span for various aspect ratios; the block shapes are also illustrated for several values of the aspect ratio. The curves represent kinematic considerations only and indicate that increasing the aspect ratio of the blocks has the effect of increasing the height of the traingular wedge and thus, for a constant block width, the volume of material that tends to move into

the excavation. The curve corresponding to an aspect ratio of 0.5 is plotted more boldly since this is the equation for the height of the arch in stratified rock according to Terzaghi.

The graph is presented without units since the axes are consistent; that is, if the span is measured in meters, then the height of the wedge will be in meters.

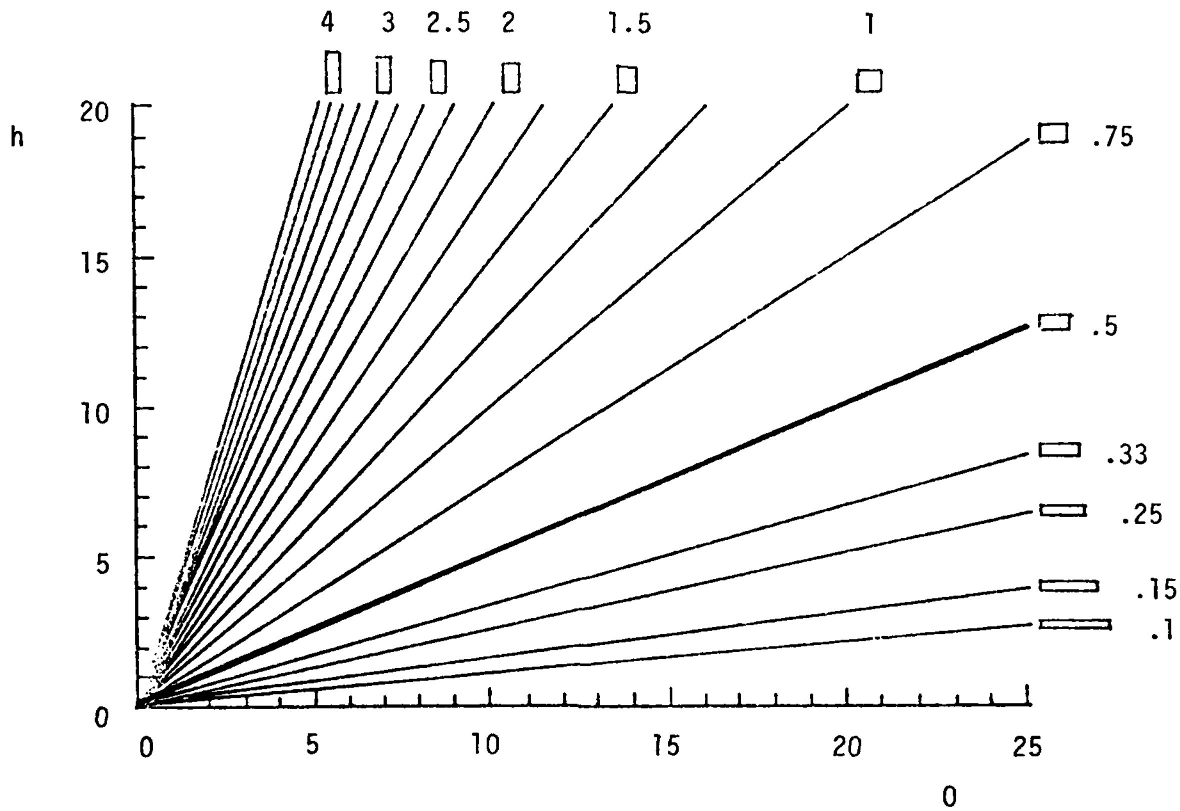



Figure 4.8 Relationship between span width (0), and height of suspended zone (h) for various values of the aspect ratio (t/w) of the model illustrated in Figure 4.3. The aspect ratio of the blocks is graphically portrayed.

### 4.4 The Stability of Roofs in the Absence of Arch Development

The simplest model of roof behavior considered comprises excavations where the roof strata form a monolithic block and resistance to downward movement of the roof strata is provided only by frictional resistance acting along the vertical sides of the block. Owing to the complete absence of flexural deformation in this model, arching behavior is unable to develop. Typical geometries of the roof block are illustrated in Figure 4.9.

In models of this type, Limit Equilibrium principles are often used to develop the governing equation (see for instance, Szechy, 1970). The idealized force distributions shown in Figure 4.9 were used to derive a relationship between the horizontal thrust (H), the total weight of the roof block (W) and the friction angle ($\phi$). In order to derive this relationship, an assumption regarding the relative magnitudes of the frictional reaction ($R_1$, etc.) must be made. To make the models illustrated in Figure 4.9 statically determinate two assumptions must be made: first, it is assumed that full frictional resistance is mobilized at all points of contact; and, second, it is assumed that the frictional resistance vectors are symmetric about the block. Under these assumptions, equilibrium principles can be used to derive the equation relating horizontal force to block weight and friction angle. This relationship is:

$$H = 1/2\ W \cot \phi \qquad 4.3$$

A number of monolithic roof geometries were analyzed by the Distinct Element method for purposes of comparison to equation 4.3. The results of these analyses are presented in Figure 4.10 where the joint plane angle of friction required for stability is plotted as

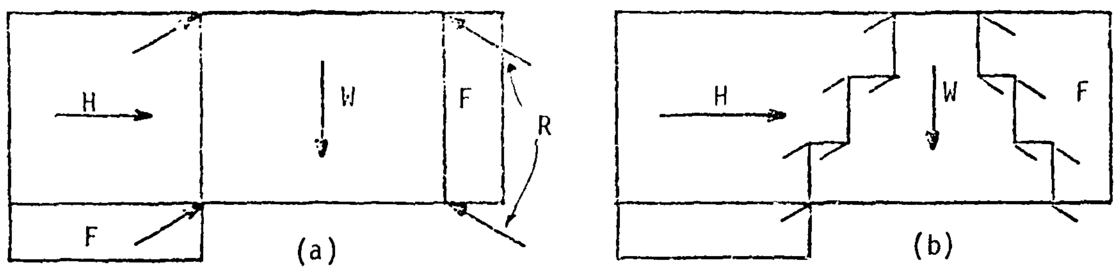



Figure 4.9 Limit Equilibrium models for roof behavior under frictional suspension.

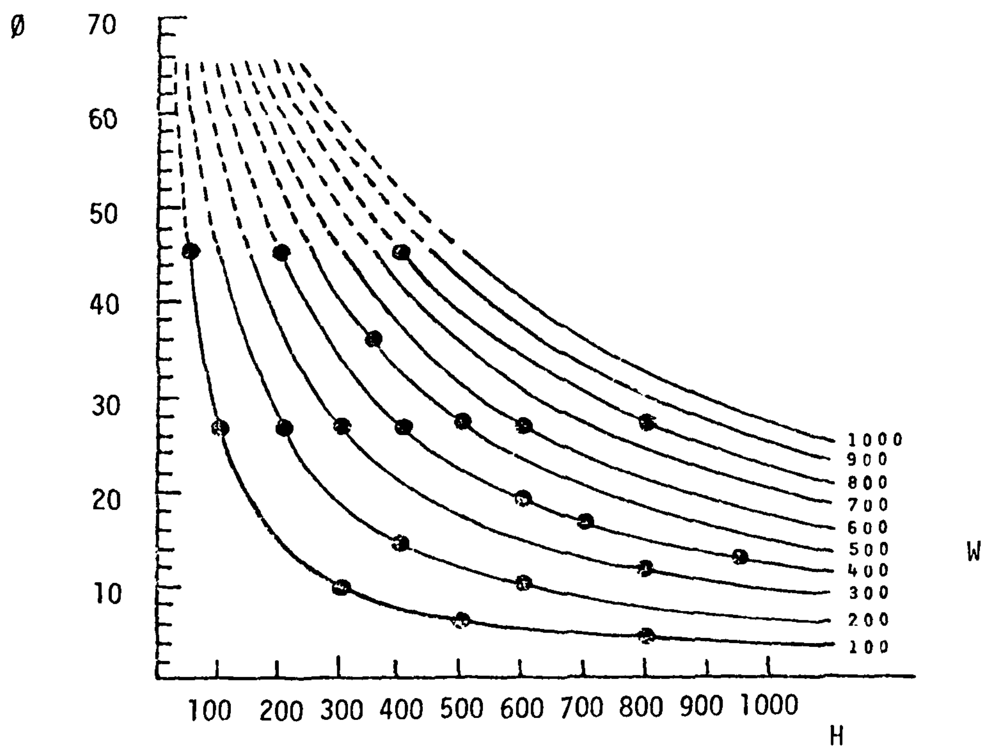



Figure 4.10 Friction angle (Ø) required for stability as a function of horizontal force (H) and roof weight (W) in a non arching model.

a function of the applied horizontal force and the roof weight. The family of curves plotted in Figure 4.10 was generated using equation 4.3; it is readily apparent upon inspection of the figure that there is a high degree of correllation between the horizontal force required for stability as calculated by equation 4.3 and that calculated by the Distinct Element method.

In the derivation of equation 4.3 it was assumed that full frictional resistance was developed at sliding contacts and that the frictional resistance developed symmetrically. Figure 4.11 illustrates that this is indeed the case; the three representative geometries presented in the figure have fully developed frictional resistances and the symmetry is obvious. The reason that some of the contact forces point away from the sliding block and that some point toward it is due to the plotting convention of the Distinct Element program. Since each contact point comprises two blocks, there must be a force acting on each block. The convention adopted is to plot the force corresponding to the edge upon which sliding is occuring.

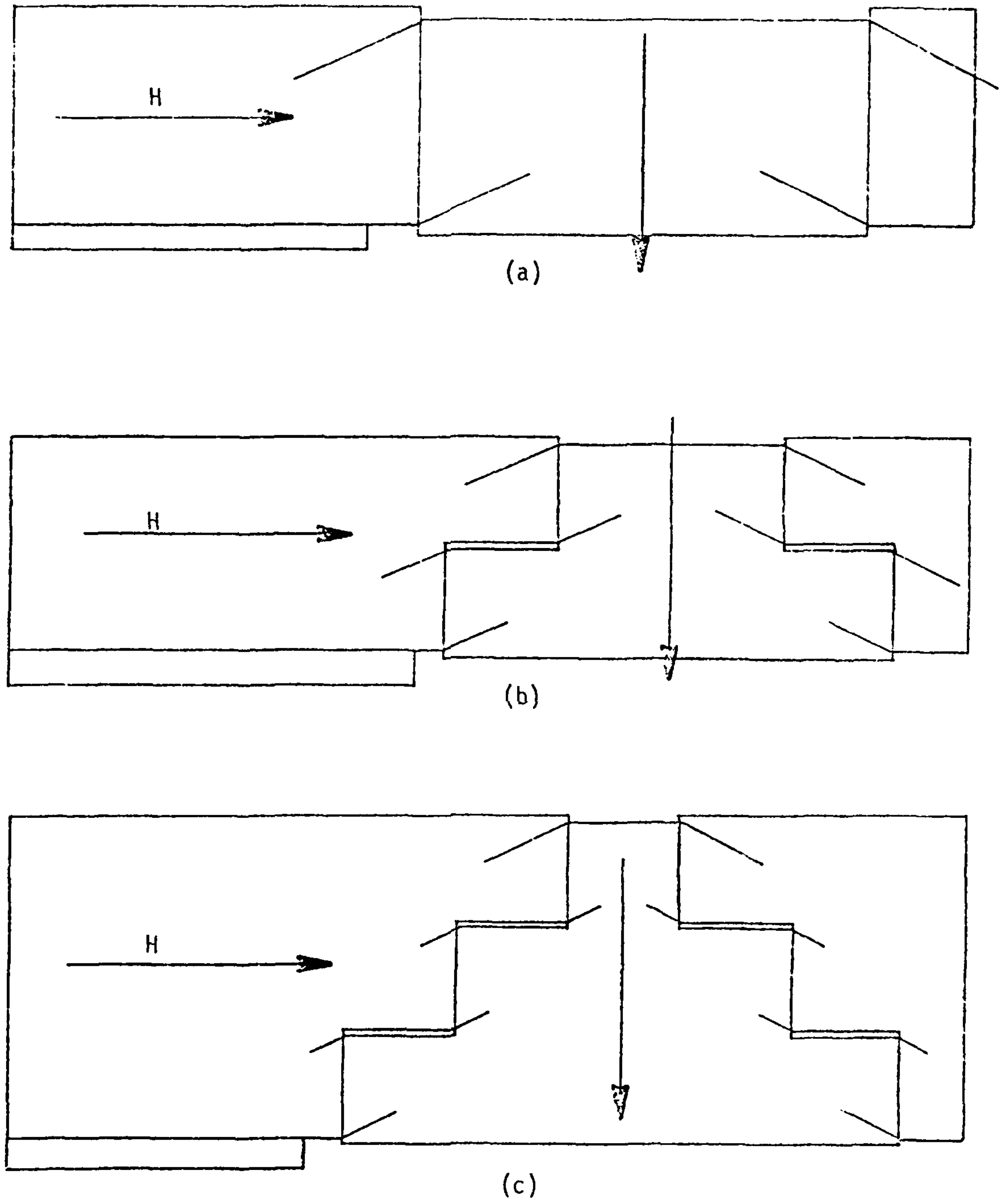



Figure 4.11 Frictional resistance developed in no-arching models at onset of sliding failure.

## 4.5 An Examination of the Stability of Jointed Roofs

### 4.5.1 The Voussoir arch

The concept of an arch is of fundamental importance in the study of the way in which loads are transfered to the sides of an opening. Relatively large, unsupported spans in jointed rock can only be obtained if the major portion of the load due to the overlying strata is carried to the abutments through arches forming in the jointed rock immediately above an excavation. As an aid in visualizing the way in which an arch develops in jointed media, it is instructive to examine a particular type of masonry structure which utilizes arch principles to transfer gravity loads to abutments. This structure is known as the Voussoir arch and examples of this type of arch can be seen in the ancient Roman aquiducts and in the vaulted ceilings of European cathedrals. The Voussoir arch is still in common use today for purposes such as relieving the loads on a lintel over a window or for bridging the span of a road.

Despite the widespread usage of the Voussoir arch in masonry construction, the first rational attempts to quantify the behavior of the Voussoir arch did not appear until Pippard, Tranter and Chitty (1936) and Pippard and Ashby (1938) published the results of an extensive experimental study of the mechanics of the Voussoir arch. A significant outcome of their research was the observation that a Voussoir arch could be analyzed as a three hinged, and thus statically determinate, arch.

The analyses performed by Pippard, Tranter and Chitty and Pippard and Ashby are significant to this present study for at least three

reasons:

1) the analysis was an attempt to quantify the behavior of a jointed medium;
2) the results of the theoretical studies were compared to physical models; and
3) the method of analysis introduces the general calculation techniques of linear arch analysis.

It would seem worthwhile, therefore, to devote some detail to the above mentioned work.

Figure 4.12 illustrates a Voussoir arch as it might occur as a structural element of a small bridge. Descriptive terminology for the various components of the arch is identified in the figure. The wedge shaped blocks which comprise the arch are individually known as voussoirs; they are usually disposed symmetrically about a central voussoir known as the keystone. Pippard and Baker (1948) summarized the earlier work of Pippard, Tranter and Chitty (1936) and Pippard and Ashby (1938) and noted that no single voussoir is more important structurally than any other and that a keystone is not an essential feature of the arch. The keystone is an aesthetic and traditional feature rather than a structural requirement; thus a Voussoir arch can be stable even with a central joint present.

As previously mentioned, the research of Pippard and his co-workers indicated that the force distribution in a Voussoir arch would be statically determinate, in the absence of fixity at the abutments, owing to the development of three hinges. For a symmetrically loaded Voussoir arch two of the hinges were seen to be loacted at the

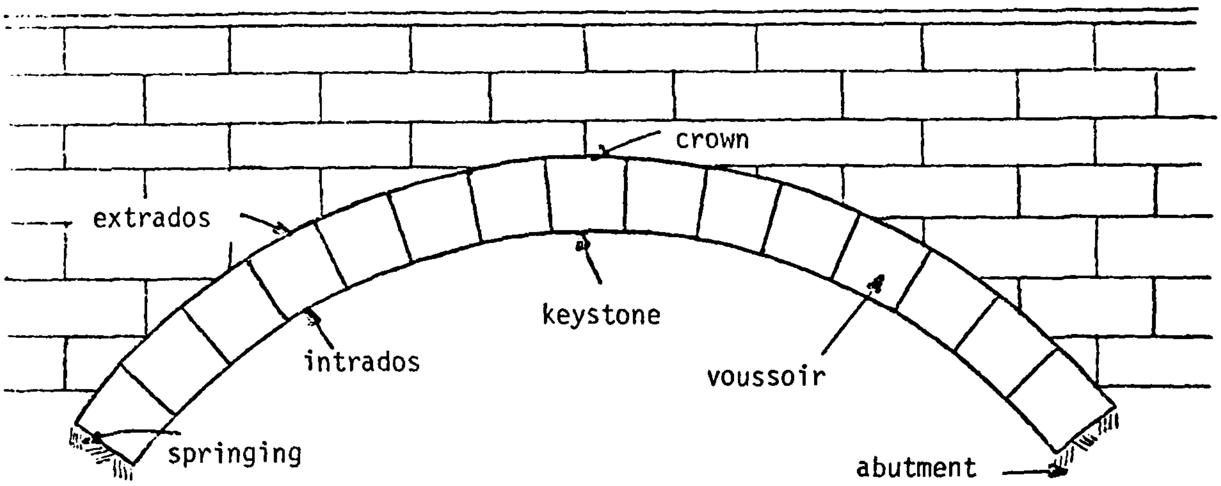



Figure 4.12 A typical Voussoir arch application with component parts identified.

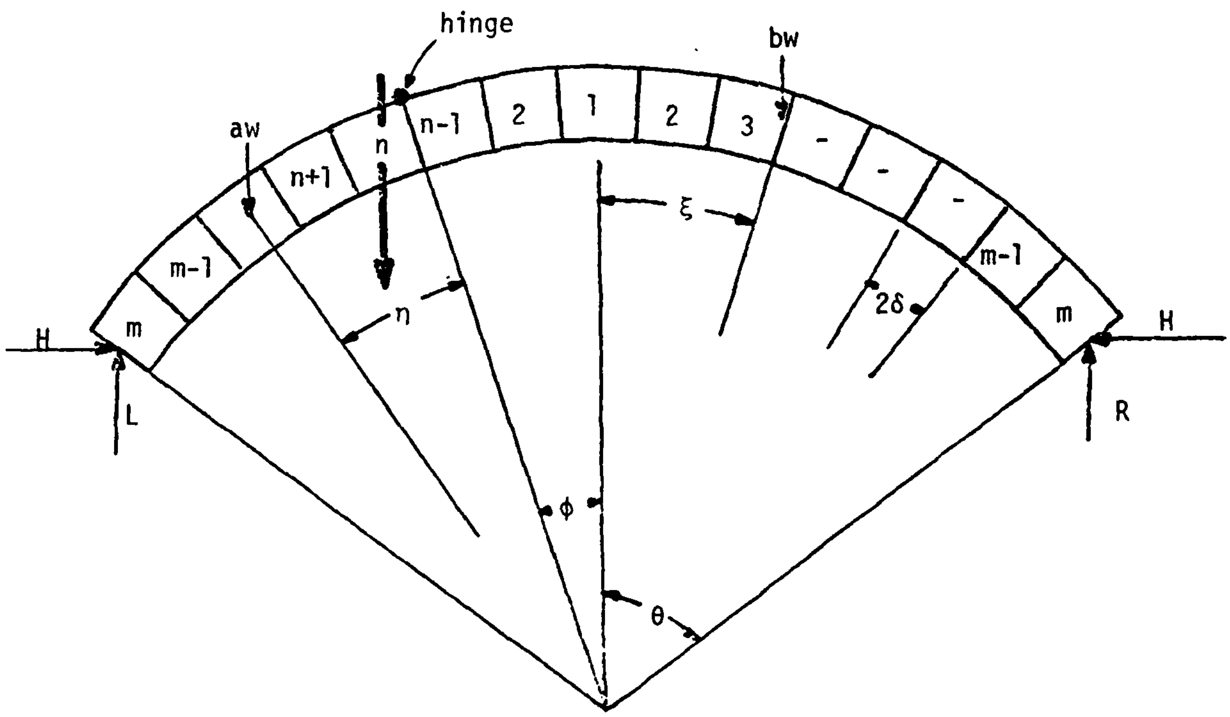



Figure 4.13 Nomenclature used in analysis of a non-symmetrically loaded Voussoir arch. For a description of identified variables see the text.

abutments with the third hinge at midspan if a central joint existed or on one of the faces of the keystone if it were present. For the case of non-symmetrical point loading the two abutment hinges developed as in the symmetrical case, but the position of the third hinge was initially variable, typically located somewhere on the extrados between midspan and the loaded voussoir. Increased load or abutment movement caused the position of the variable hinge to move closer to the loaded voussoir; when the hinge reached the joint next to the loaded voussoir on the midspan side, it did not change its position again until failure had occured.

The observations concerning the formation of hinges, coupled with the results of the other analytical and experimental studies performed by Pippard and his co-workers provide good data for checking the accuracy of the Distinct Element method as well as introducing the techniques of linear arch analysis which will be used extensively in this chapter.

The idealized model used in the present study is illustrated in Figure 4.13. The model arch is circular in shape and the abutments subtend an angle of $2\theta$. Hinges are assumed to develop at the abutments and at the extrados of the joint nearest the point of application of the external load W on the side nearest the crown. Each individual voussoir subtends an angle of $2\delta$ and has a weight $w$. The voussoirs are numbered consecutively from 1 at the keystone to m at the abutment; thus the total number of voussoirs in the arch is 2m-1. In addition to the external load, the arch is also loaded by

its self weight. With respect to the non-abutment hinge, self weights of magnitude aw and bw act on the shorter and longer spans respectively, as illustrated in Figure 4.13. The points of application of the loads are located as follows: the external load W is applied at the centroid of voussoir number n; the longer span load is located at an angle $\xi$ clockwise from the vertical; the shorter span load is located at an angle $\eta$ counter clockwise from the hinge which in turn is located at an angle $\phi$ counter clockwise from the vertical. It is easily shown that for an odd number of voussoirs;

$$\begin{aligned} \eta &= \xi = (m - n + 1)\,\delta; \\ \phi &= (2n - 3)\,\delta; \\ \theta &= (2m - 1)\,\delta; \\ a &= m - n + 1; \text{ and} \\ b &= m + n - 2 \end{aligned} \tag{4.4a}$$

For a Voussoir arch with an even number of voussoirs a slight modification must be introduced; the voussouirs are numbered consecutively from the crown joint starting with 1 and ending with m. Thus, these are 2m voussoirs in the arch. The corresponding parameters are given by:

$$\begin{aligned} \eta &= \xi = (m - n + 1)\,\delta; \\ \phi &= 2(n - 1)\,\delta; \\ \theta &= 2\,m\,\delta; \\ a &= m - n + 1; \text{ and} \\ b &= m + n - 2 \end{aligned} \tag{4.4b}$$

The analytical approach used by Pippard, Tranter and Chitty (1937) involved the determination of strain energies and application of Castigliano's theorems. This approach was necessary because they

were interested in displacements as well as forces and because they analyzed indeterminate as well as determinate arches. Since the present study is limited to three hinged arches which are statically determinate, a simpler analytical method has been adopted. Equilibrium principles provide the means to determine the force distribution in a statically determinate structure and have been used to derive the following equations.

The horizontal force H induced by a point load of magnitude W applied at the centroid of voussoir n subject to the development of hinges in the manner previously described is found by the superposition of the horizontal force $H_w$ due to the external load and the horizontal force $H_s$ due to the self load. These horizontal forces are calculated by taking moments about the midspan hinge and using an equation expressing vertical equilibrium.

The horizontal thrust due to the self weight of the arch is given by:

$$H_s = \left((\sin\theta - \sin\phi)\, L_s - aw\,(\sin(\phi + \eta) - \sin\phi)\right)\frac{1}{\cos\phi - \cos\theta} \qquad 4.5$$

The quantity $L_s$ represents the vertical abutment reaction on the shorter span due to the self weight of the arch and is given by:

$$L_s = \left((\sin\phi + \sin(\theta + \eta))\, aw + (\sin\theta - \sin\eta)\, bw\right)\frac{1}{2\sin\theta} \qquad 4.6$$

The horizontal thrust due the applied point load is given by:

$$H_w = \left(L_w\,(\sin\theta - \sin(\phi + \delta)) - W(\sin(\phi + \delta) - \sin\phi)\right)\frac{1}{\cos\phi - \cos\theta} \qquad 4.7$$

The quantity $L_w$ represents the vertical abutment reaction on the shorter span due to the point load and is given by:

$$L_w = \frac{W}{2} \left( 1 + \frac{\sin (\phi + \delta)}{\sin \theta} \right) \qquad 4.8$$

To demonstrate the validity of the above equations, several data points from Pippard and Baker (1948) are plotted in Figure 4.14a with the plotted curve representing the ratio of horizontal force to applied load, neglecting the self weight of the arch, given by equations 4.7 and 4.8. Since Pippard and Baker did not present their analytical expressions for the ratio of horizontal thrust to applied load, the parameters used in equations 4.7 and 4.8 were scaled from drawings in their paper. In light of this limitation, the fit of the data points to the theoretical expression can be described as quite good.

The Distinct Element method was used to analyze several Voussoir arches. The results of one of these series of tests are presented in Figure 4.14b. The theoretical curve presented in the figure represents the horizontal force due to an applied point load, incorporating the horizontal force due to the self weight of the arch, as given by equations 4.5 through 4.8. In this case, as in other Voussoir arches analyzed by the Distinct Element method, the test points fit the theoretical curve quite well, and suggest that the Distinct Element method is capable of reproducing the results of the physical model tests performed by Pippard and his co-workers.

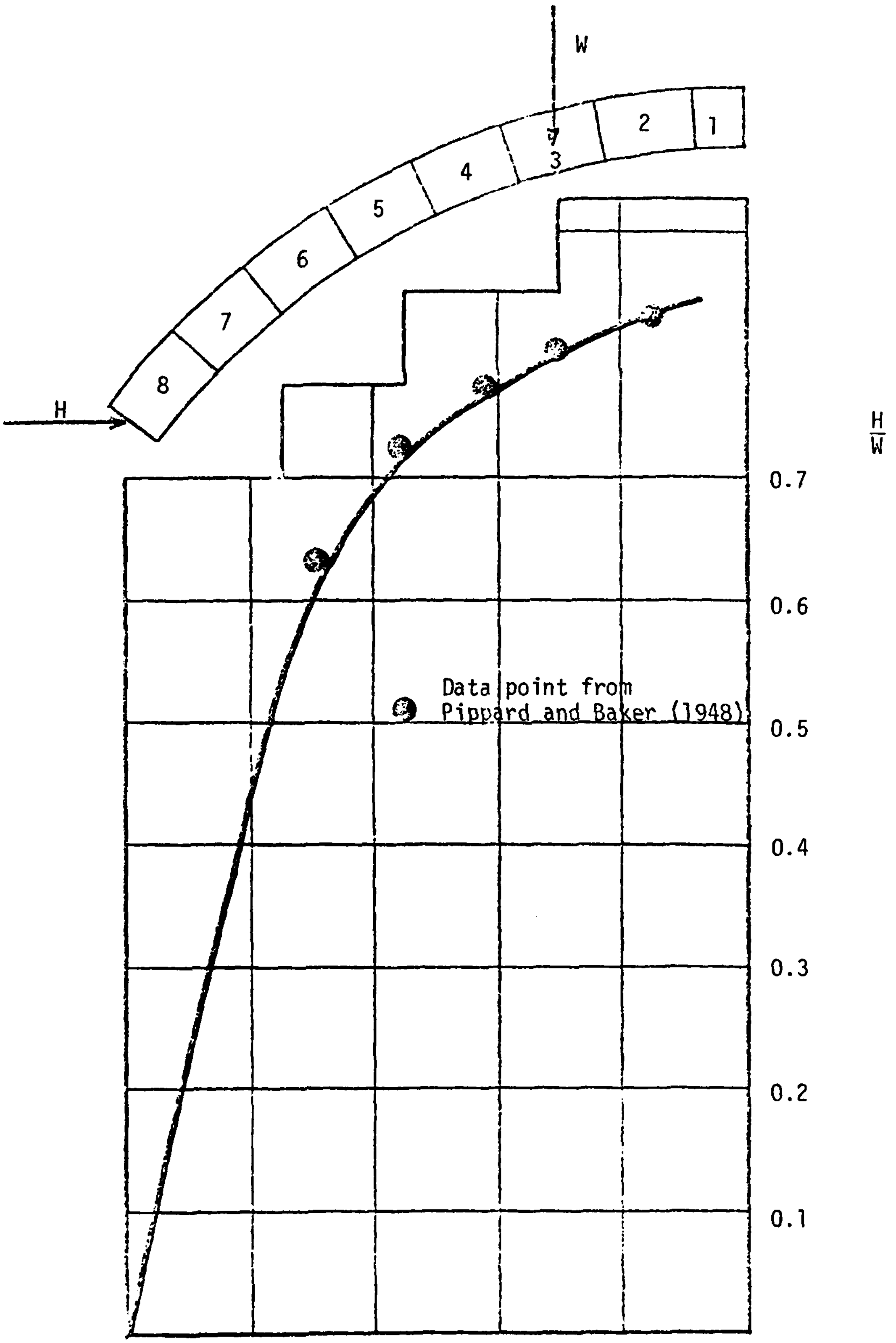



Figure 4.14(a) Horizontal thrust developed due to an applied point load neglecting the self weight of the arch.

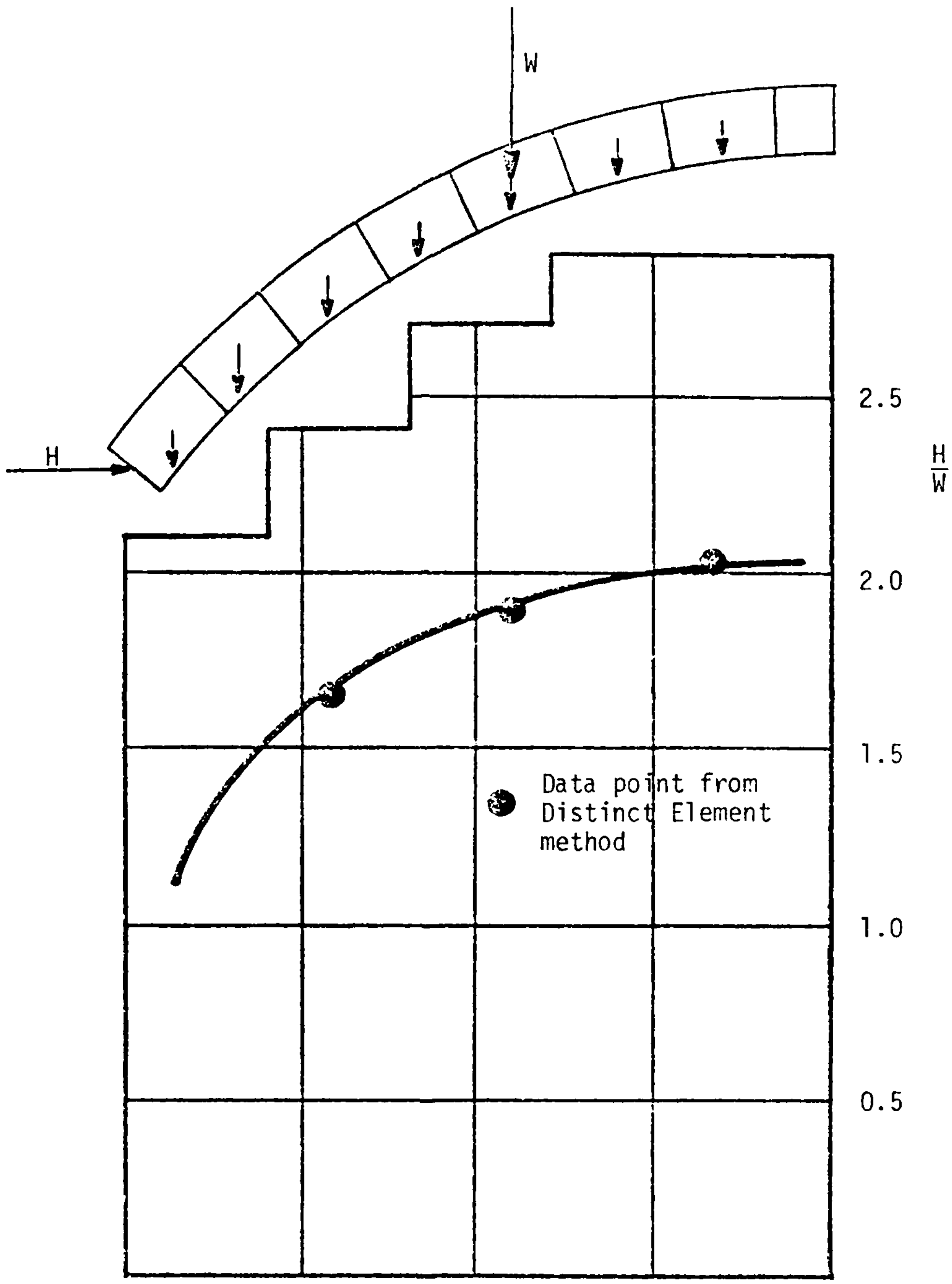



Figure 4.14(b) Horizontal thrust due to an applied point load incorporating the self weight of the arch.

To complete the discussion on Voussoir arches it is instructive to examine the force distribution in the arches for several cases as calculated by the Distinct Element method. The geometry of the arch and two force distributions for different positions of the applied point load are presented in Figure 4.15; also shown in the figure is the geometry of the arch at failure in response to increased load. Immediately apparent in both force distributions is the formation of the midspan hinge as evidenced by absence of contact force on one corner of the loaded block. Pippard and Ashby (1938) concluded that the position of this hinge was invariable once finite displacement of the abutments or sufficient loading had occured. As previously noted, the hinge always formed on the extrados of the arch on the midspan side of the block to which the point load had been applied; in all of the arches analyzed by the Distinct Element method the midspan hinge was seen to develop in the manner described by Pippard and Ashby.

The force distribution in the arch is also indicative of the way in which the failure of the arch ultimately occurs in response to increased loading. Examination of the force distributions in Figure 4.15 (b) and (c) show that in both cases the longer span is experiencing far less compressive force on the extrados than on the intrados. As the externally applied load is increased to induce failure, the geometry shown in Figure 4.15(d) develops. The increased load leads to the development of a fourth hinge on the arch at which point the arch collapses. The position of the fourth

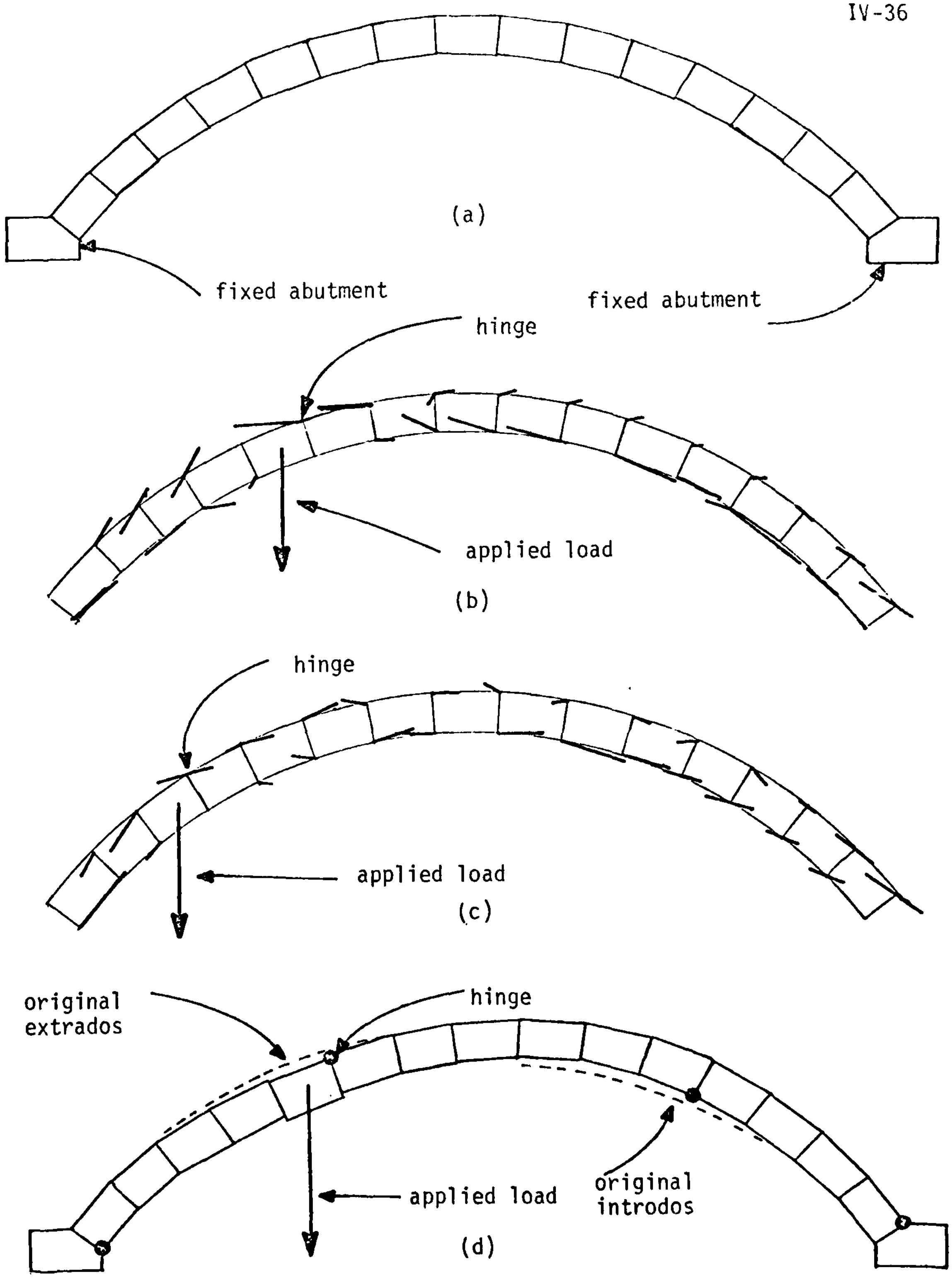



Figure 4.15 Variation in force distribution with the position of the applied load, and the ultimate collapse of a Voussoir Arch.

hinge is not as predictable as the other three, and is complicated by the fact that slippage may occur along the sides of the voussoirs. The method of calculation of the critical external load, which involves trial and error procedures and is beyond the scope of this brief introduction to Voussoir arches, is discussed by Pippard and Baker (1948).

### 4.5.2 Arching conditions in jointed roofs

As early as 1885 (Jones and Davies, 1929) Fayol demonstrated that an arching action could occur in bedded roofs and would act to shield the immediate roof from the full weight of the overlaying material. The fact that the height of the dome formed when a mine roof failed was limited was taken by Jones and Davies as further evidence that arching action was occurring and acting to transfer the bulk of the vertical load to the adjacent pillars. At a later date, Evans (1941) proposed that arching was also occurring within the immediate roof in the manner of a Voussoir Arch.

Evans characterized the behavior of the lower strata in a mine roof as a jointed beam within which the stresses were distributed in the manner of a modified three hinged arch. As downward displacement of the beam occurs, the central joint opens in response to "bending" induced tension and the compressive forces are increased at the upper contact. The analogy to a three hinged arch is clearly seen in the postulated pressure distribution which is illustrated in Figure 4.1. Because the manner in which the forces are distributed

resembles the classical Voussoir arch, this type of analysis is often referred to as Voussoir beam analysis.

Evans' research, and that which followed, was concerned with the stress state and subsequent fracture of the strata within the immediate roof above the excavation and is not directly applicable to the present study. The concept of two separate pressure arches in the roof strata is, however, of interest.

In the discussions that follow, the pressure arch that carries the weight of the superincumbent strata to the sides of the excavation will be termed the ground arch; the lower arch that forms within the wedge of failing material will be termed the roof arch.

The analyses that form the basis for the discussion presented in this chapter indicate clearly that the stability of the roof of an excavation in jointed material is dependent upon the formation of the roof arch. In fact, the general pattern of force distribution in the basic model of this study is that illustrated in Figure 4.2(d). Most of the weight due to the overlaying strata is transferred to the abutments through the ground arch; the stability of the resulting destressed zone is maintained through the development of the roof arch in the lower strata. Specific departures from this general pattern were observed in those instances where the horizontal stress field was greater than that required for stability and in those instances where the block thicknesses exceeded some critical thickness. Both of these occurrences inhibit block rotations and thus the development of arching.

Although it may be argued that the geometry of the basic model forces the development of the ground arch in the manner of a corbel, the following examples demonstrate the formation of both arches even in those cases where the geometry of the blocks does not act to aid the formation of the ground arch.

Before proceeding with the discussion it is appropriate to mention a factor common to all of the Distinct Element models presented in this chapter. The horizontal stress field is modeled by means of loads applied at the centroids of the outermost blocks. Additionally, these blocks are modeled as having no frictional resistance to lateral movement. The result of this approach is that the horizontal stress thus has the characteristics of a "following load"; the horizontal stress field always remains constant and is independent of lateral displacement. This simplification was necessary because the rigid blocks of the Distinct Element formulation do not allow blocks peripheral to the excavation to accomodate movement through elastic strain. If this approximation is not made, the modeled geometries are so stiff that failure does not occur. The analyses therefore cannot model the effects of varying the joint stiffness or of the dilatant properties of real joints. The analyses do, however, closely approximate the conditions modeled by linear arch analysis and are considered to be valid, though rudimentary, approaches to modeling the behavior of excavation roofs.

Figure 4.16(a) illustrates an example of the basic model; if complete failure were to take place, blocks from the lower six

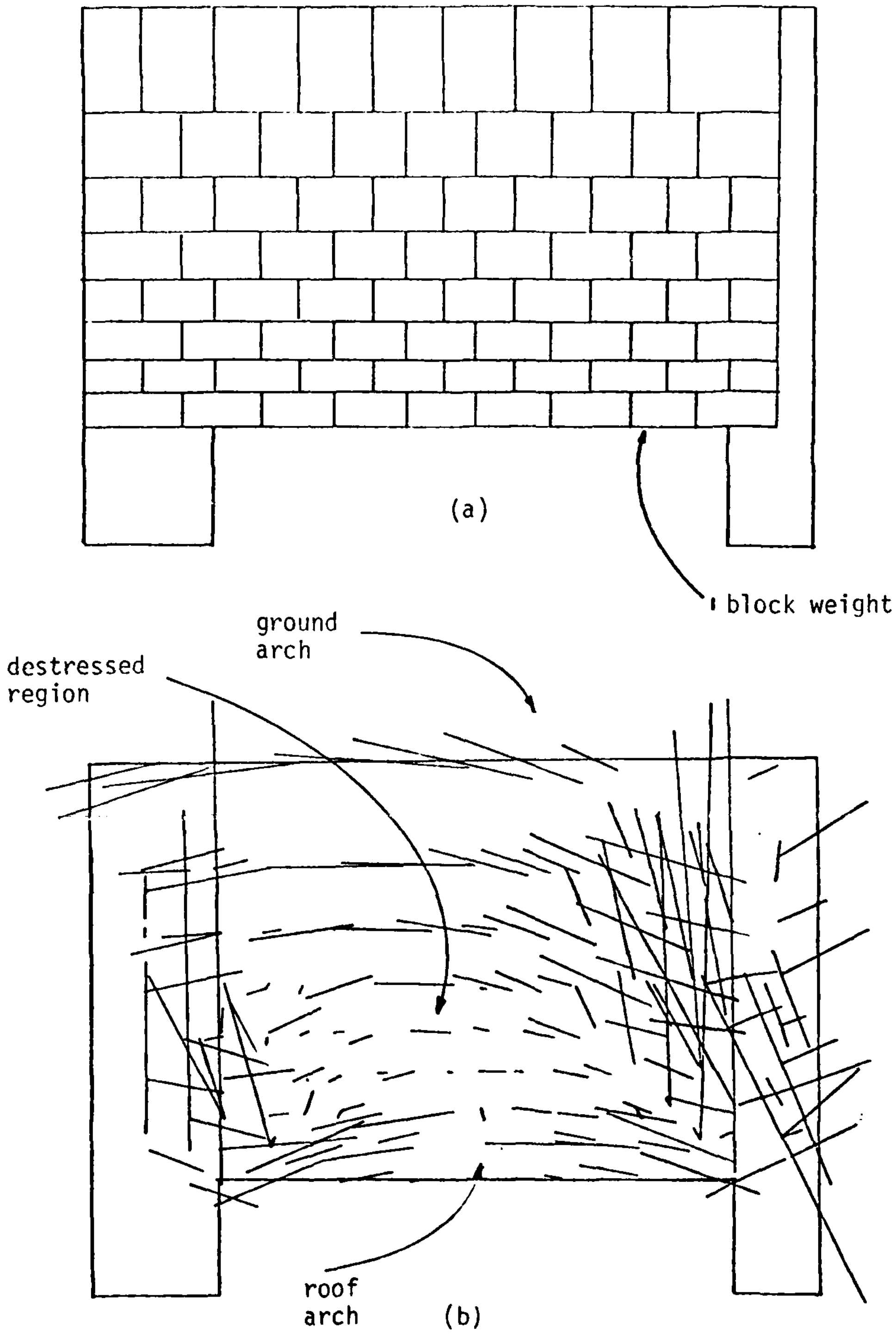



Figure 4.16 Formation of the ground and roof arches in a vertically discontinuous jointed model.

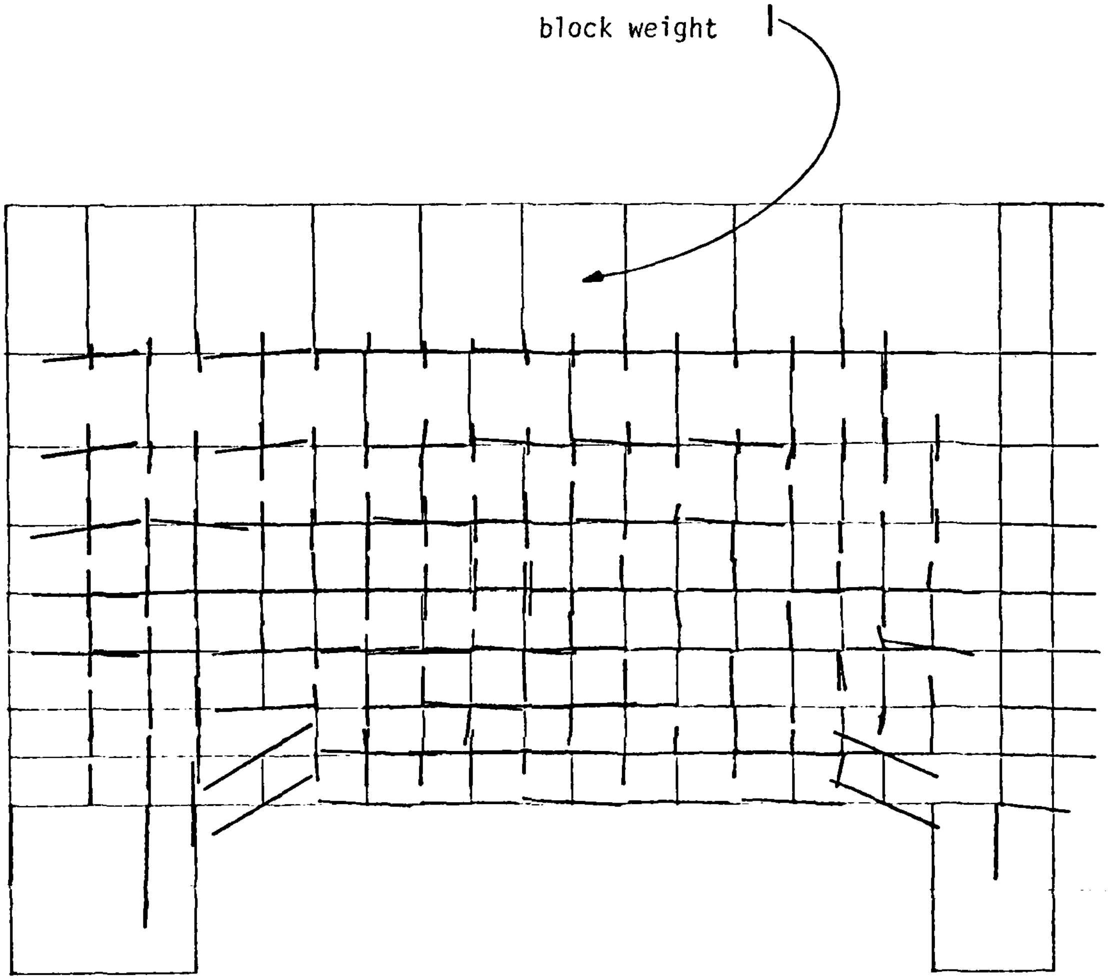



Figure 4.17 Roof and ground arch development inhibited due to high horizontal forces.

rows would move into the excavation. However, sufficient horizontal pressure is present so that the configuration is just stable. The distribution of contact forces is as illustrated in Figure 4.16(b).

Although examination of Figure 4.16(b) indicates that the middle joint in the lowest row of blocks has opened at its lower contact, the configuration of blocks is, nevertheless stable. The mechanism that is responsible for this stability is the development of the roof arch. The relaxed or suspended zone can be seen to extend upward roughly four-fifths of the span distance.

The magnitude of the horizontal force has a significant effect upon the behavior of the blocks in the lower roof. Figure 4.17 illustrates the same geometry as Figure 4.16(a) but in this case the horizontal force has a greater magnitude. The force distribution indicates that full contact is maintained across the central joint of the immediate roof and that stability of the roof is due solely to frictional support at the abutments in the manner of a monolithic roof.

Significant arching has not developed in this model but the amount of horizontal force necessary to prevent arch formation and thus support the roof by frictional resistance alone is approximately twice as large as that required for stability under conditions where the roof arch develops. It should be noted that if the lower roof comprised a single block, the amount of force required to stabilize the configuration by frictional resistance would be less than the case where arching develops.

Two examples where the jointing pattern does not involve

corbelling are included in this section. These examples demonstrate the development of both the roof and ground arch in two instances where the geometry of the rock mass does not necessarily act to force the development of two arches. Figure 4.18(a) illustrates a model with continuous jointing in the horizontal and vertical directions subjected to a horizontal force just sufficient to maintain equilibrium. The resulting force distribution is illustrated in Figure 4.18(b); the behavior of the roof is again characterized by a relaxed zone extending upwards roughly two-thirds the width of the span. This zone is supported by the roof arch. The ground arch is clearly developed but not to the same degree as would be expected in the previous model, where the geometry of the model aids the development of the ground arch.

Figure 4.19(a) illustrates a model geometry with continuous vertical jointing but discontinuous jointing horizontally; as with the model shown in Figure 4.18, the continuity of the vertical jointing was expected to inhibit the formation of the ground arch and allow the mass to fail monolithically. The force distribution, however, indicates that once again, both the ground arch and the pressure arch have formed and led to the characteristic relaxed zone, although in this case the height of the relaxed zone extends only one-third of the span upwards into the roof.

The block movements that lead to the development of arches are primarily of a rotational nature. The rotations arise as the unequal forces on opposite sides of a block,which arise as the blocks move ,

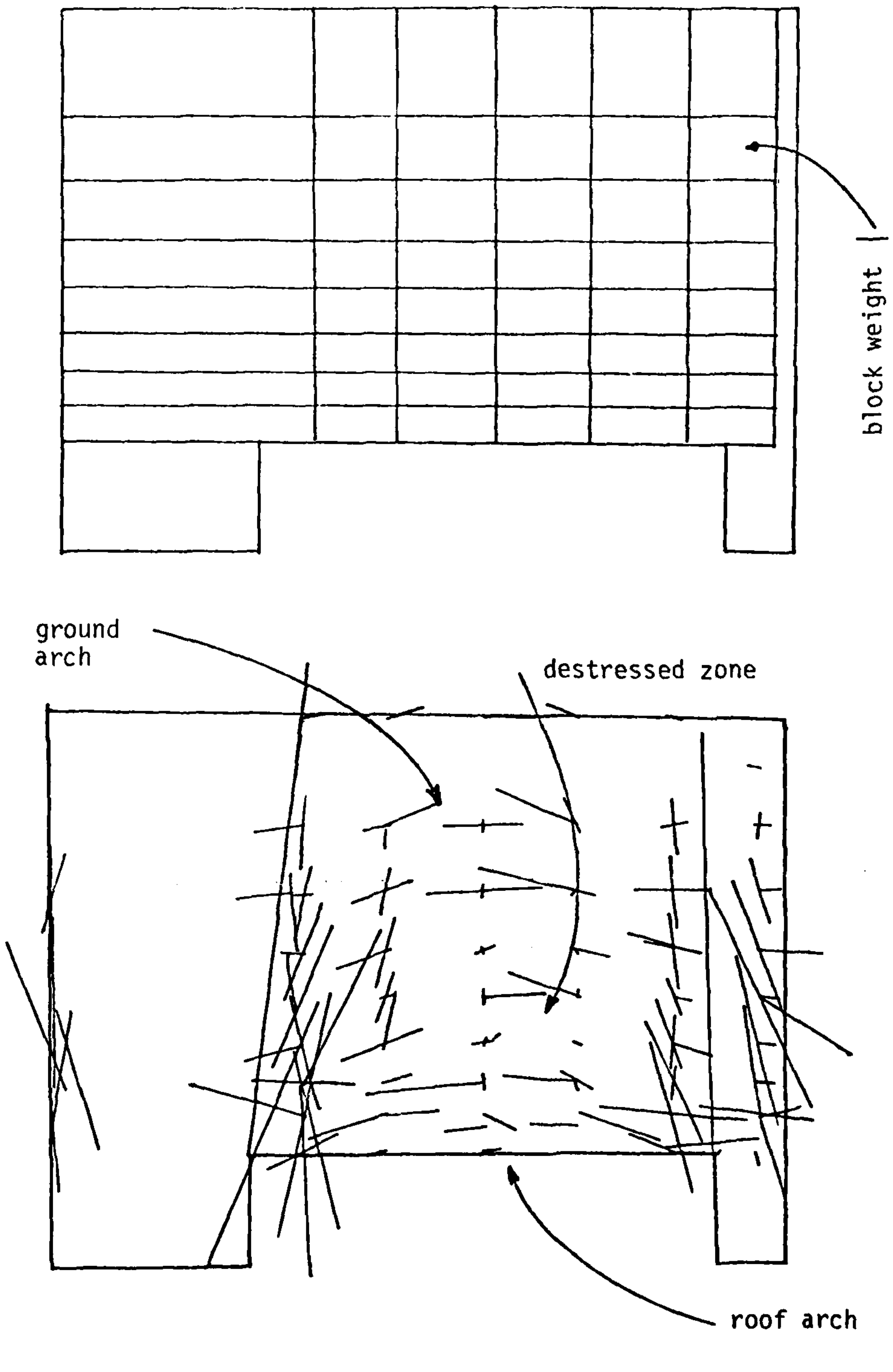



Figure 4.18 Formation of ground and roof arches in a continuously jointed model.

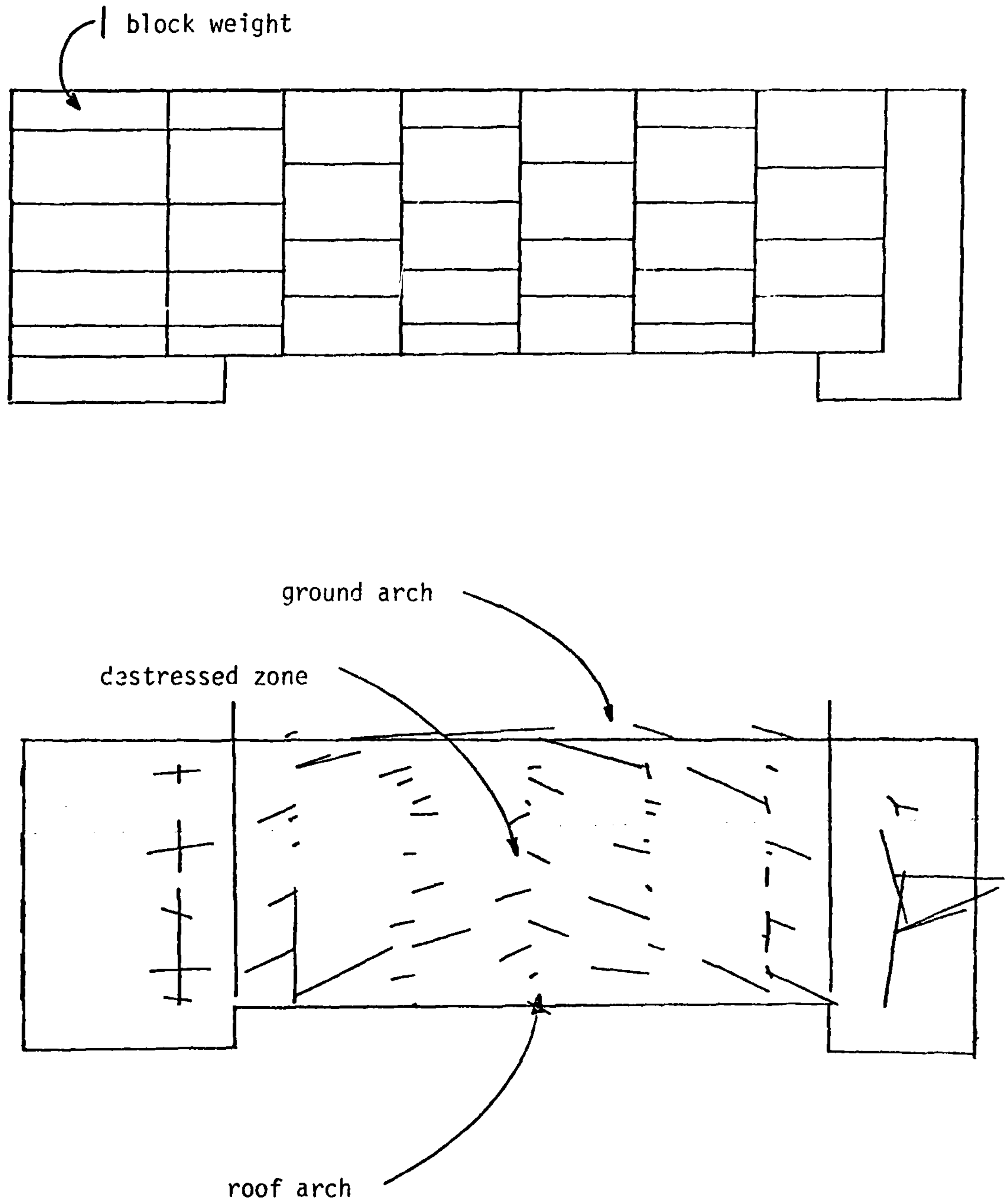



Figure 4.19 Formation of the ground and roof arches in a horizontally discontinuous jointed model.

cause a moment imbalance about the centroid of the block. In the case of a stable configuration, equilibrium is maintained through horizontal thrust whereas in an unstable configuration, the rotation can continue since sufficient equilibrating forces cannot be developed. Figure 4.20 illustrates a block geometry (a), the contact force distribution (b) and the block rotations (c) corresponding to the contact force distribution. Comparison of (b) and (c) indicates that: all significant rotation is occurring within the suspended zone; the magnitude of the rotational movement decreases with depth into the roof; and, contact forces within the suspended zone are primarily normal to joint surfaces even though this is where the most significant rotation has occurred. The development of the ground arch as seen in Figure 4.20(b) indicates that the suspended zone extends approximately four rows of blocks into the roof. The development of the roof arch can also be seen. Considering the relative magnitudes of the rotations of the blocks maintaining these arches, it is interesting to note that larger forces are developed in the ground arch even though the rotations are smaller. This is probably a reflection of the higher degree of confinement of the blocks maintaining the ground arch. The blocks adjacent to the excavation are free to rotate somewhat into the excavation. The next row of blocks upward thus has the freedom to rotate toward the excavation although not as much as the lower row. Successively less rotation is permitted until at the limit of the suspended zone, minimal rotation is occurring.

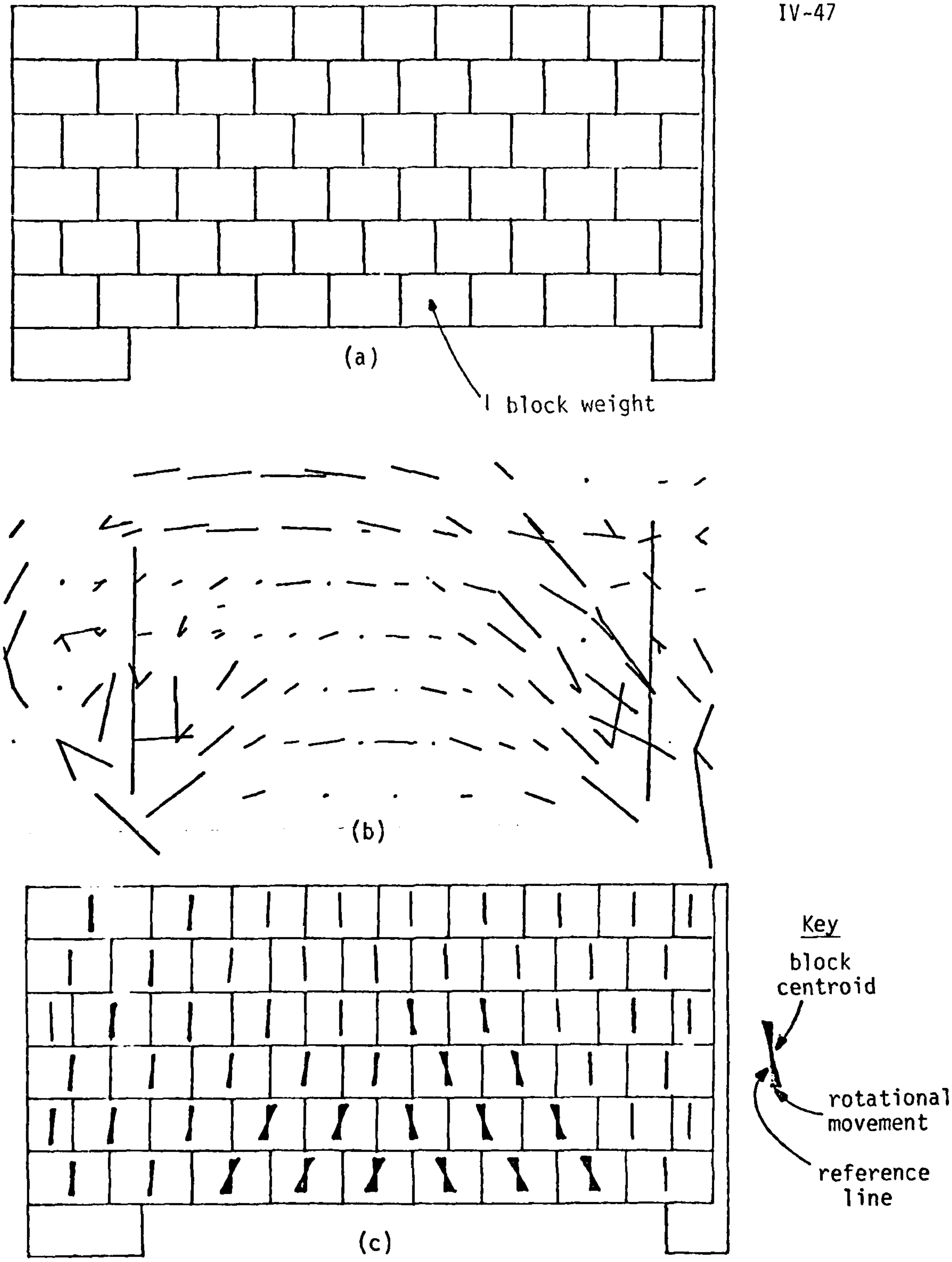
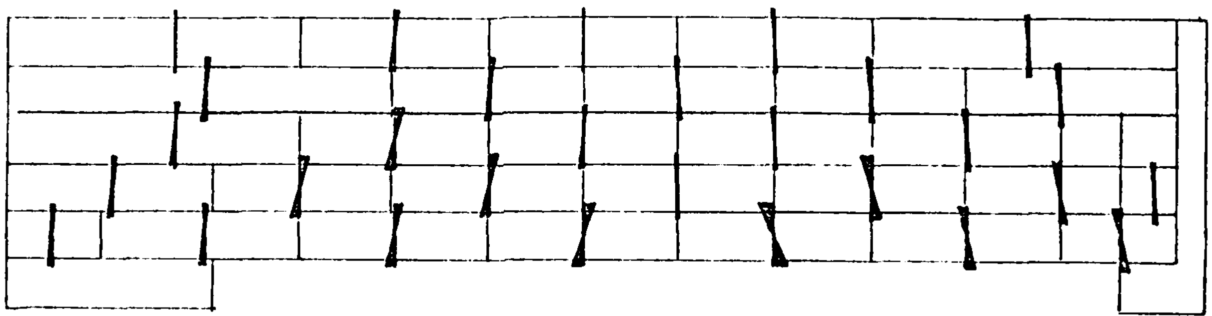
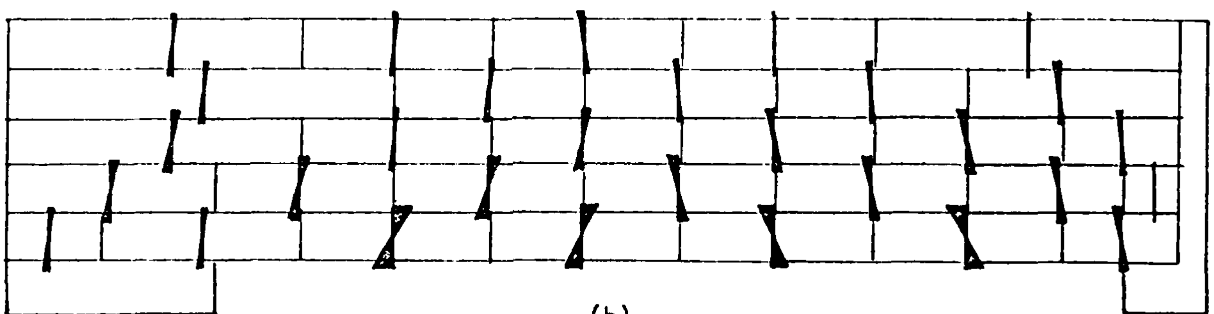



Figure 4.20 Contact forces and corresponding block rotations.



(a)

condition at equilibrium



(b)

condition at failure

Figure 4.21 Development of block rotation as failure initiates.

As failure conditions develop, further rotation occurs as can be seen in Figure 4.21. The most significant change in rotation occurs in the lowermost row where the magnitude of the rotations of the inner two blocks of the lower row remain constant but those of the outer two blocks increase to a value greater than that of the inner blocks. This deflection then allows the blocks in the next row upward to deflect and rotate, effectively moving the loosened or suspended zone upward.

### 4.5.3 The development of arching in single layer models

The development of arches in mine roofs is often explained by recourse to simple models from linear arch theory (e.g. Woodruff, 1966) such as those illustrated in Figure 4.23. The force distribution in this type of model is that of a three hinged arch and can be readily deduced as the model is statically determinate. Consider the left hand side of the symmetric model as illustrated in Figure 4.22, vertical equilibrium shows V = W, and moment equilibrium about point a shows:

$$H = \frac{WO}{4t} \qquad 4.9$$

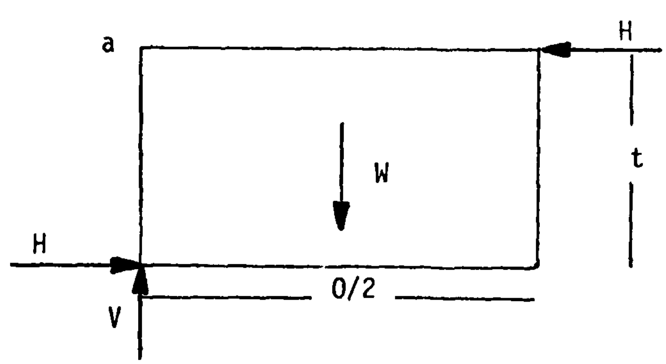



Figure 4.22 The Linear Arch Model

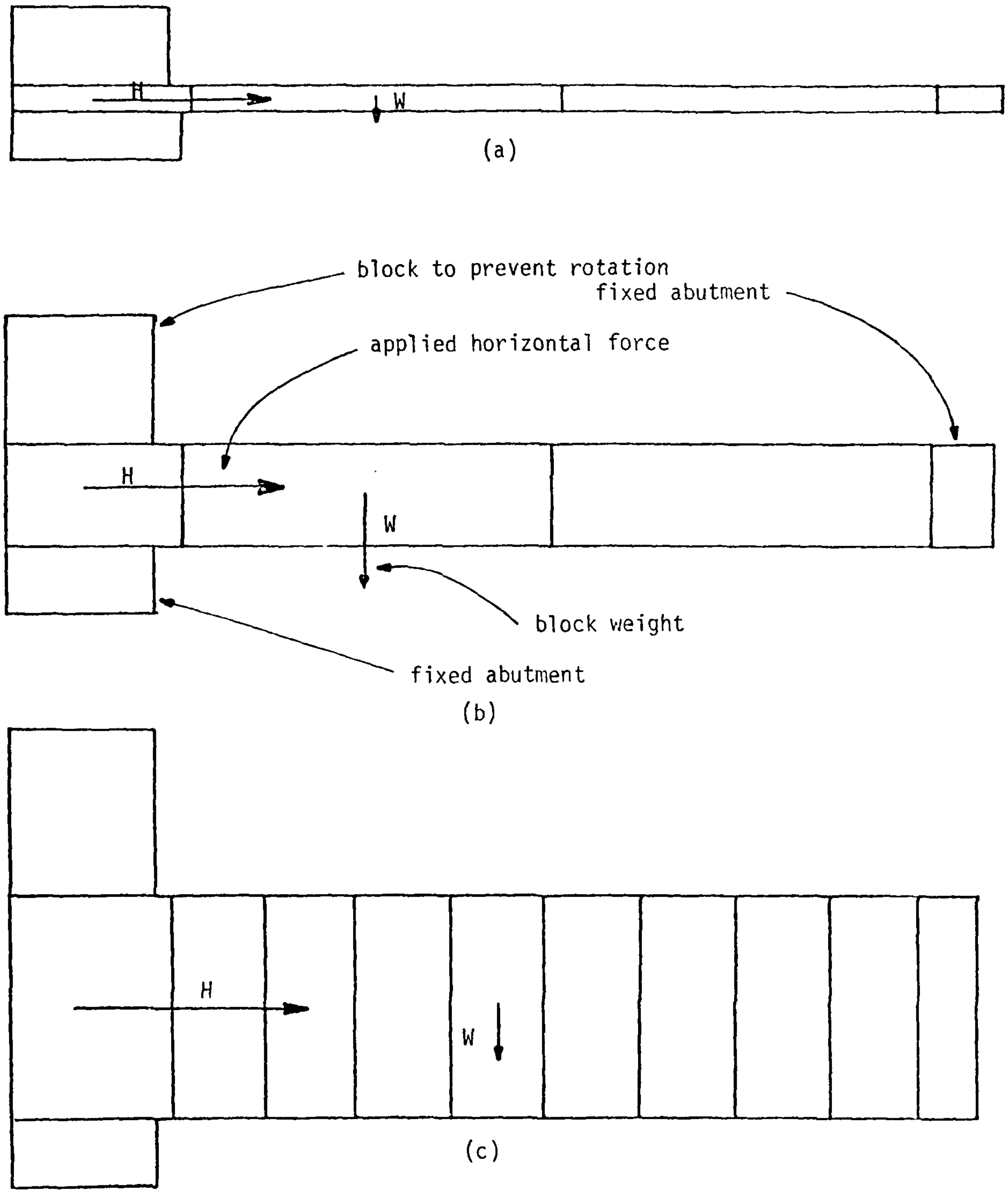



Figure 4.23 Typical block models for linear arching study.

This force distribution represents a limiting condition; as vertical deflection of the beam causes the contact at the lower face to be broken, the value of the lever arm t decreases and thus an increasing value of H is required for stability.

Analyses by the Distinct Element method of several linear arch models is summarized in Table 4.1 and indicates that Equation 4.9 may be used to predict the horizontal thrust required for stability in certain instances. These data show that equation 4.9 is correct for low aspect ratios of the blocks but loses validity as block thicknesses increase and friction coefficients of the joints decrease. For larger block thicknesses and lower friction coefficients, the horizontal thrust required for stability is found accurately by equation 4.3 which is repeated here for convenience:

$$H = W/2 \cot \phi \qquad 4.3$$

Analysis of the force distribution at failure provides insight into this discrepancy. Figure 4.24 illustrates the force distribution at failure in models C, A and D. Figure 4.23(a) illustrates conditions at failure for model C with $\mu = 0.5$. Full frictional resistance is mobilized on the abutment joints and compression is transmitted across the lower contact of the mid span joint. Although arching is developing, failure is by sliding along the abutment joints. Figure 4.24(b) illustrates the force distribution for model A with $\mu = 1.0$. Arching is fully developed as evidenced by the absence of force transmittal at the lower mid span joint contact. An important distinction in this case is the fact that frictional resistance is

Table 4.1 Summary of Linear Arch Models

| Model | Friction Coefficient μ | Predicted Failure Loads | | Observed Side Load at Failure | Observed Failure Mode |
|---|---|---|---|---|---|
| | | Arching[4] | Sliding | | |
| A[1] | .25 | 500 | 280 | 500[2] | Arching |
| | .5 | 500 | 140 | 500 | Arching |
| | 1.0 | 500 | 70 | 500 | Arching |
| B | .25 | 500 | 550 | 550[3] | Sliding |
| | .5 | 500 | 280 | 500 | Arching |
| | 1.0 | 500 | 140 | 500 | Arching |
| C | .25 | 500 | 1120 | 1110 | Sliding |
| | .5 | 500 | 560 | 550 | Sliding |
| | 1.0 | 500 | 280 | 490 | Arching |
| D | .25 | 500 | 2580 | 2550 | Sliding |
| | .5 | 500 | 650 | 650 | Sliding |

Notes:

1 Geometry of models

Model A t = 25, 0 = 700, 2 block linear arch model
Model B t = 50, 0 = 700, 2 block linear arch model
Model C t =100, 0 = 700, 2 block linear arch model
Model D t =225, 0 = 700, 8 block, voussior beam

2 Difference in calculated side load for arching models is typically less than 2%.

3 Difference in calculated load for sliding models is typically less than 1%.

4 Equation 4.1 may be rewritten by recognizing that W is a function of t and 0 ($W = t \times \frac{0}{2} \times d$); substitution leads to (density, d = 1) $H = \frac{0^2}{8}$ and thrust is thus independent of block thickness.

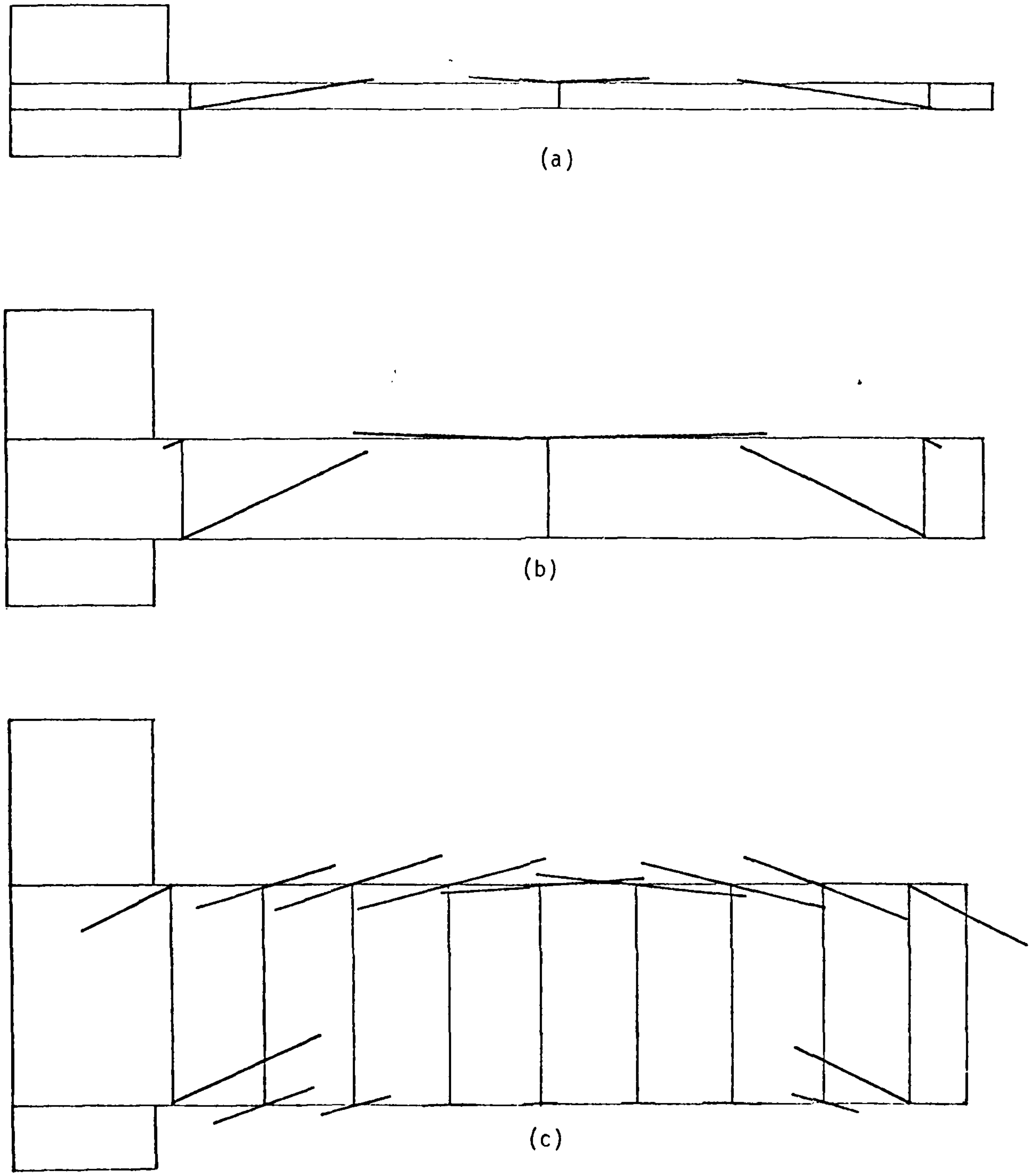



Figure 4.24 Force distributions in linear arch model (force scale from Figure 4.23).

not fully developed along the abutment joints. The vertical component of the abutment reaction is equal to the weight of the roof block while the horizontal component is equal to the horizontal thrust required to maintain stability against arching (equation 4.9).

This fact permits the calculation of the critical friction coefficient that delineates arching failure from frictional sliding in the linear arch model. Consider an opening of span O, with the roof blocks having thickness t, and weight W per block. From linear arch theory, the thrust developed during arching is:

$$H = \frac{WO}{4t} \tag{4.9}$$

The critical friction angle ($\phi$ crit) is the inverse tangent of the ratio of the block weight and the thrust force:

$$\phi \text{ crit} = \tan^{-1}\left(\frac{4t}{O}\right) \tag{4.10}$$

If the friction angle of the joints is greater than this critical value, sliding cannot occur and failure, if it occurs, will be by true arching. On the other hand, if the friction coefficient on the joints is less than this critical value, sufficient frictional resistance cannot be developed and failure occurs by sliding.

Equation 4.10 is plotted in Figure 4.25; this figure may be used to determine if, for a given span and block thickness, failure will be by true arching or by slippage with only partial development of arching conditions. The equation has been found to be correct for all linear arch models analyzed.

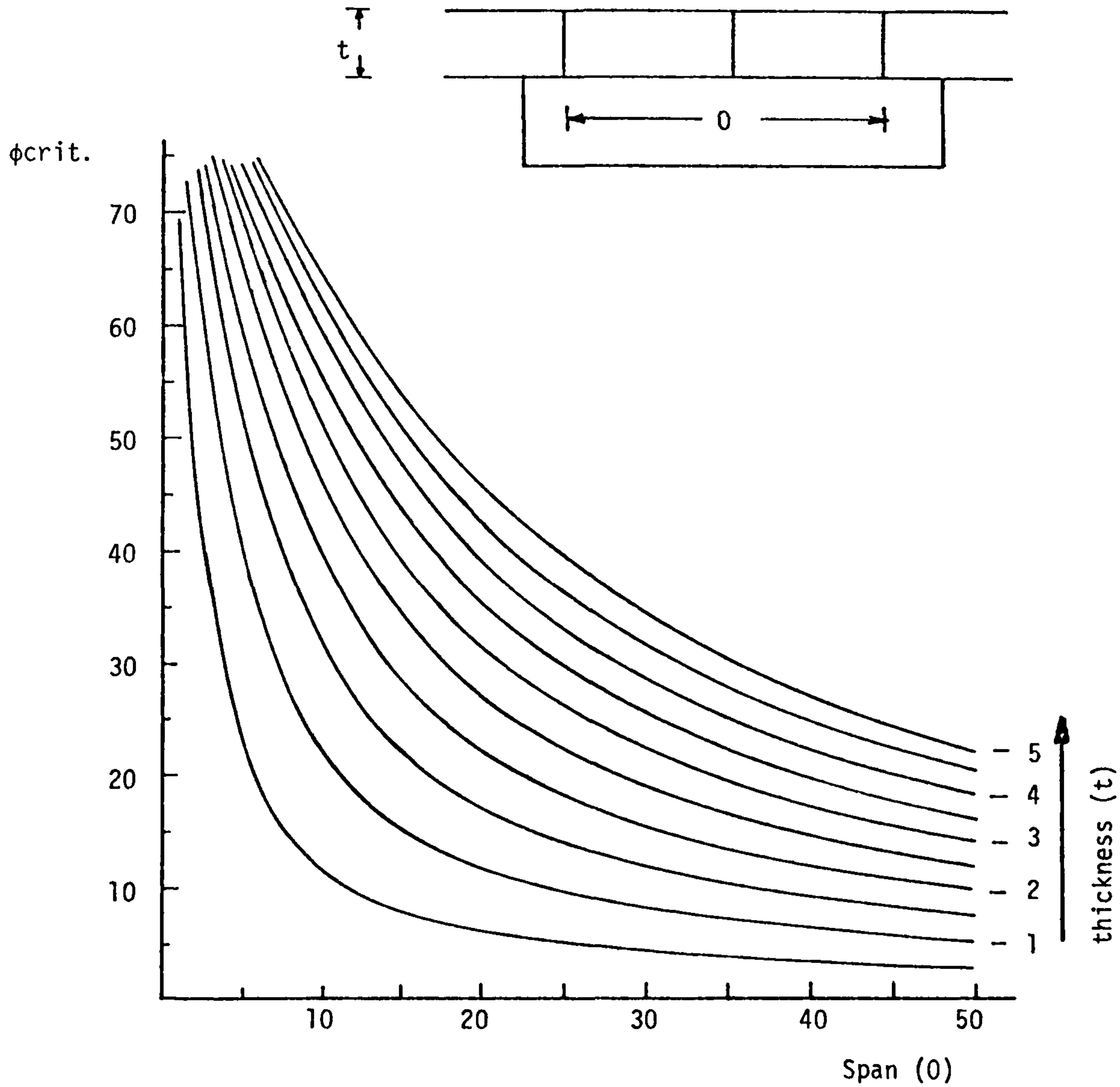



Figure 4.25 Critical friction angle as a function of excavation span and block thickness (span and thickness must be in consistent units).

4.5.4 Arching in multilayered models

In the preceeding section relationships were developed that were found to predict accurately the horizontal thrust required for stability and the failure mode for the single layer, linear arch or Voussoir beam model. The application of these relationships to multilayered models has not been as successful. Figure 4.26 illustrates a summary of stability conditions for a number of tests of the basic model geometry. Whereas in the linear arch model, comprising a single layer of blocks, errors in the predicted failure load were less than 2% for arching failure and less than 1% for sliding failure, the corresponding errors for the multilayer cases were as much as 40% for arching cases but still less than 1% for sliding cases. Pertinent data of the multilayer tests are summarized in Table 4.2.

It is prudent at this time to digress momentarily to discuss the origin of the data presented in Table 4.2. In a typical stress analysis the relationship between the parameters can be expressed as an equation and a unique answer obtained by some solution technique (viz. inverting the stiffness matrix in a Finite Element analysis). In the Distinct Element method, as in other nonlinear explicit methods, the problem geometry is defined, the boundary conditions are specified and subsequent motion of the blocks is observed; equilibrium occurs as the force distribution converges to a situation where the relative accelerations of the blocks approaches zero. In terms of the problem at hand this means that a set of

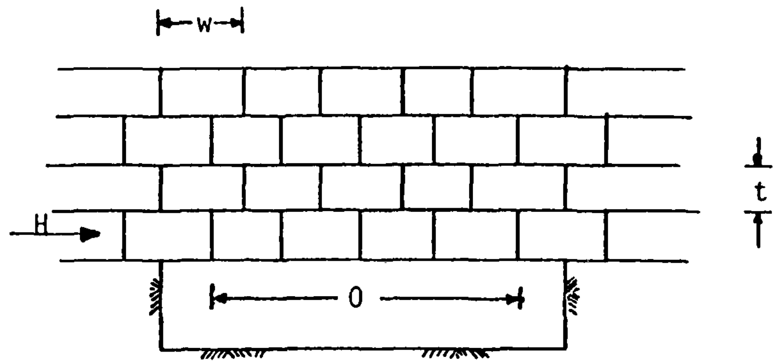
Table 4.2

Summary of Multilayer Arching Tests

| | | | | Predicted Side Loads (H) at Failure [2] | | | | | | Observed Side Loads (H) at Failure [4] | | | | Observed Failure Mode [5] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| O [1] | t | b | W | Arching | $\mu$=1.0 | $\mu$=0.5 | $\mu$=0.3 | $\mu$=0.25 | $\phi$ crit [3] | $\mu$=1.0 | $\mu$=0.5 | $\mu$=0.3 | $\mu$=0.25 | |
| 700 | 20 | 1 | 106 | 460 | 53 | 106 | 176 | - | 0.11 | 55 | 105 | 175 | - | S,S,S |
| 700 | 20 | 2 | 106 | 460 | 53 | 106 | - | 212 | 0.11 | 385 | 425 | - | 465 | A,A,A |
| 700 | 20 | 3 | 110 | 480 | 55 | 110 | 185 | - | 0.11 | 440 | 470 | 515 | - | A,A,A |
| 700 | 20 | 4 | 110 | 480 | - | 110 | 193 | - | 0.11 | - | 540 | 650 | - | -,A,A |
| 750 | 20 | 6 | 120 | 560 | 60 | 120 | - | 240 | 0.11 | 650 | 725 | - | 800 | A,A,A |
| 700 | 40 | 2 | 230 | 500 | 115 | 230 | - | 460 | 0.23 | 300 | 315 | - | 415 | A,A,A |
| 700 | 50 | 4 | 290 | 420 | - | 290 | - | - | 0.29 | - | 575 | - | - | -,A,- |
| 700 | 50 | 2 | 285 | 500 | 143 | 285 | - | 570 | 0.29 | 475 | 560 | - | 600 | A,A,A |
| 600 | 50 | 2 | 230 | 345 | 115 | 230 | - | - | 0.33 | 300 | 350 | - | - | A,A,- |
| 600 | 40 | 4 | 196 | 360 | - | 196 | - | - | 0.25 | - | 300 | - | - | -,A,- |
| 500 | 50 | 2 | 180 | 225 | 90 | 180 | - | - | 0.40 | 200 | 225 | - | - | A,A,- |
| 450 | 25 | 4 | 85 | 190 | 43 | 85 | - | 170 | 0.22 | 150 | 175 | - | 200 | A,A,A |
| 800 | 100 | 2 | 610 | 570 | 305 | 610 | - | 1220 | 0.50 | 325 | 625 | - | 1225 | S,S,S |
| 800 | 100 | 1 | 610 | 570 | 305 | 600 | - | 1220 | 0.50 | 305 | 615 | 0 | 1210 | S,S,S |

Notes:

1. O is the true span, t is block thickness, b is number of blocks in lower row of strata and W is total weight of blocks in lower row. All dimensions are consistent computer units.
2. Predicted side loads (H): Arching failure load from equation 4.9, Sliding failure loads, for various values of friction coefficient $\mu$ from equation 4.6.
3. Critical friction angle delineating sliding and arching, equation 4.10.
4. Load (H) observed at failure in Distinct Element model for several tests of same geometry.
5. Observed mode of failure (S - sliding, A - arching) for each of the tests of same geometry. Columns correspond to high, medium and low value of joint friction coefficient. "-" indicates no test data for that value of $\mu$.



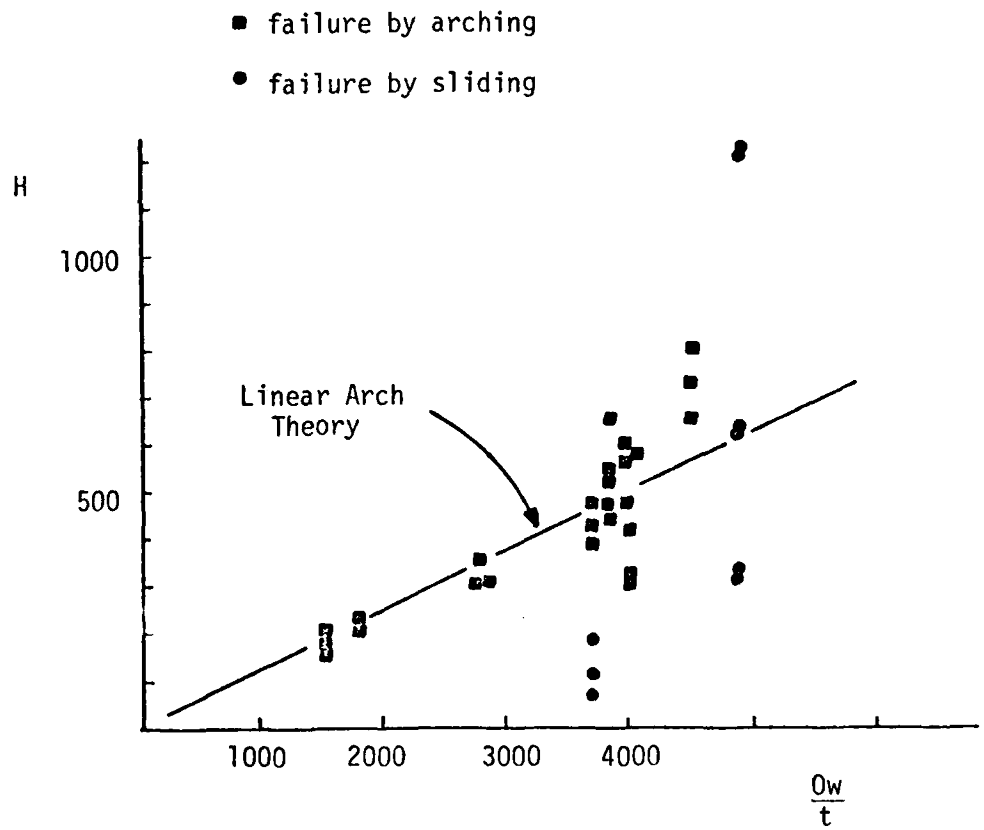




Figure 4.26 Summary of multilayer arching tests (all dimensions in computer units).

boundary conditions is applied and the program allowed to run until it is determined that the geometry is stable. The boundary conditions are then incrementally modified and again the program is allowed to run. This iteration is then continued until failure occurs. Thus, each data point on Figure 4.26 represents a limiting condition deduced by a minimum of four or five computer runs.

The problem of determining equilibrium conditions is discussed further in Appendix B.

Tabulated in Table 4.2 are predicted side loads for stability obtained by Equation 4.9 for arching conditions and by Equation 4.6 for sliding conditions. The observed loads at failure are also tabulated and comparison indicates a general divergence from the predicted values. Nine of the tests developed sliding failure modes and are indicated by a circular symbol in the plot of Figure 4.26; the remainder of the tests developed full arching failure modes and the data points are seen to follow the general trend of the linear arch model as represented on Figure 4.26 by the square symbols.

In those tests where failure was by frictional slippage, the side loads were typically within 2% of the value predicted by Equation 4.6; the indication being that in those cases where full arching does not develop, Equation 4.6 may be used to assess the stability of a mine roof. For those tests where stability is dependent upon full development of the roof arch however, the error relative to the predicted side loads ranges from about 5% to 40% with the average error equal to approximately 17%. The only consistent trends in the errors are that the error increases with

the number of blocks in the lower row and that for a fixed geometry the error either increases or moves from negative to positive as the friction angle increases.

Analysis of the linear arch, single row models led to the calculation of a critical friction angle (Equation 4.10) that was found to predict accurately the dividing line between failure by arching and failure by sliding along the abutment joints. The tangent of the critical friction angle for each of the multilayered block tests is also tabulated in Table 4.2; several instances can be found in the table which illustrate discrepancies between actual and predicted failure modes with arching failure modes developing in several instances where the critical friction angle concept predicted a sliding failure mode.

Examination of the data indicates that failure by full development of the roof arch is more likely to occur than failure by sliding along the abutment joints. Exceptions to this observation were found only in those instances where the development of the arch was somehow constrained. Specific conditions that lead to failure by slippage were the expected case where the main roof was monolithic and arching could not develop, and cases where the block thickness was relatively large and the main roof comprised only two blocks. In these instances the horizontal load at failure could be predicted accurately in terms of the block weights by the use of Equation 4.3:

$$H = 1/2 \, W \cot \phi \qquad 4.3$$

The most noticeable departure from the observed behavior of the single layer linear arch models was concerned with contact force distribution along the lower row of blocks. In the single layer models, failure always initiated as the central contact along the lower face opened; as noted earlier, this was the expected behavior since the deflection of the blocks reduced the moment arm of the horizontal stabilizing force resulting in increasingly unstable conditions. This phenomonon is, however, not indicative of the behavior of the multilayer models.

The conditions preceeding failure in the multilayer models are characterized by two common features. First, loss of force transmittal across the lower contact of the midspan joint is not indicative of failure. Frequently, significant horizontal force reduction after the joint opens is required before failure occurs. The second general behavior pattern that was recognized concerns the distribution of contact forces in the immediate roof. Figure 4.27 presents a typical multilayer model and a section of its contact force distribution. The blocks are in equilibrium but a reduction in the horizontal thrust of approximately 10% would lead to failure; this is a typical force distribution of a multilayer model at stress conditions slightly greater than those at which failure occurs. Three characteristics of the force distribution in multilayer models have been noted in all models tested and are indicated in Figure 4.27 by the letters A, B, and C. The characteristics are:

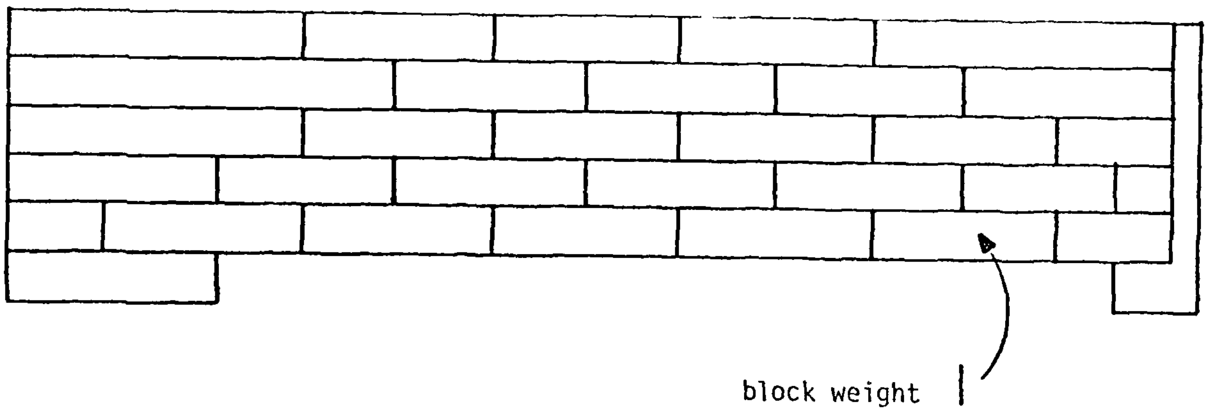
A) absence of force transmittal across the lower contact of the mid span joint

B) minimal vertical transmittal within the suspended zone, especially to the lower row of blocks

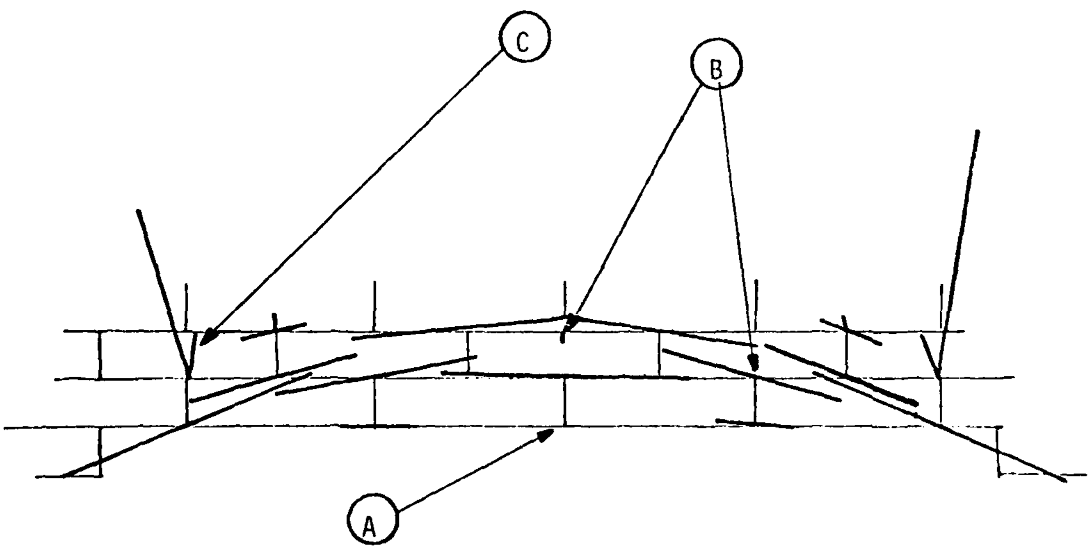
C) the development of an additional contact force where the blocks adjacent to the abutment rotate into the next upward level of blocks

The second characteristic is to be expected in light of the model; the corbelling effect of the blocks outside of the suspended zone acts to lessen the span over which the next row of blocks must be supported. In this particular case, the span is decreased by 25%, the weight to be supported is decreased by 25% and the required horizontal force to just maintain equilibrium is 45% of that which is actually being applied. This simple calculation neglects the vertical force transmittal which is occuring to the second row of blocks, but the fact that the thrust applied to the second row of blocks is almost twice that required for stability indicates why the deflection of the second row is small compared to that of the lower row and thus why no vertical force transmittal occurs to the lower row.

The other two observations, A and C, are closely related and provide a reasonable explanation as to why the behavior of the multilayer models depart from the linear arch model. Figure 4.28 is a schematic representation of the two blocks on the left hand side of the lower row of blocks in Figure 4.27(a) based on the contact force distribution of Figure 4.27(b). The linear arch model is based upon the contact force distribution illustrated in Figure 4.22; comparison of these two figures indicates that the model used




(a)




(b)

Figure 4.27  Contact force distribution in lower rows of multilayer model.

for the development of the linear arch equation is not valid for the multilayer cases. As the lower row of the multilayer model deflects some rotation of the blocks occurs and leads to the development of a shearing resistance along the top of the block. The same phenomenon was observed in the Goodman and Bray Limit Equilibrium Model of toppling behavior of rock slopes (section 3.6). In the Goodman and Bray model the corresponding force was taken as zero; although this may be valid for the low degree of confinement that exists in near surface problems, the stress conditions surrounding an underground excavation dictate an elastic interaction of the blocks. Two blocks cannot just "sit" next to each other but must act to transmit relatively high forces across their boundaries. Thus, as the block attempts to rotate it is resisted not only by the mid span contact force but by an additional shearing resistance as well. This observation explains the reason for the inability of the linear arch model to predict accurately the horizontal load at failure: the linear arch model simply does not consider all of the forces present. The presence of an additional shearing resistance also explains how stable conditions can be maintained even though the lower contact of the mid span joint is broken. In section 4.3.5 it was noted that in the linear arch model, once this contact opened, the governing equation dictated that failure must occur. The presence of the additional force acting on the block tends to maintain equilibrium in a manner not accounted for by the linear arch model.

Unlike the linear arch model, the force distribution presented

in Figure 4.28 is statically indeterminate. To develop an equation relating span, block thickness, joint spacing, block weights and friction coefficient would require that two assumptions be made concerning the forces. The logical assumptions would be to assume the development of full frictional resistance of the two contacts experiencing shear. However, in the majority of tests run, full frictional resistance was not seen to develop at either contact. Rather, the Distinct Element method can be used to study each model on an individual basis and develop relationships not subject to arbitrary assumptions regarding the force distributions.

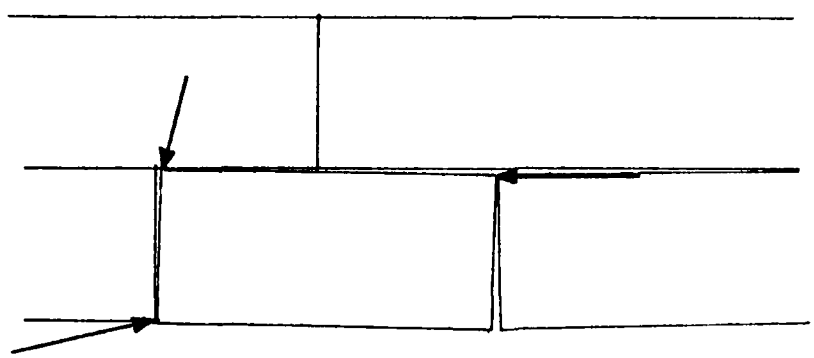


Figure 4.28 Force distribution observed during arching in multilayer models.

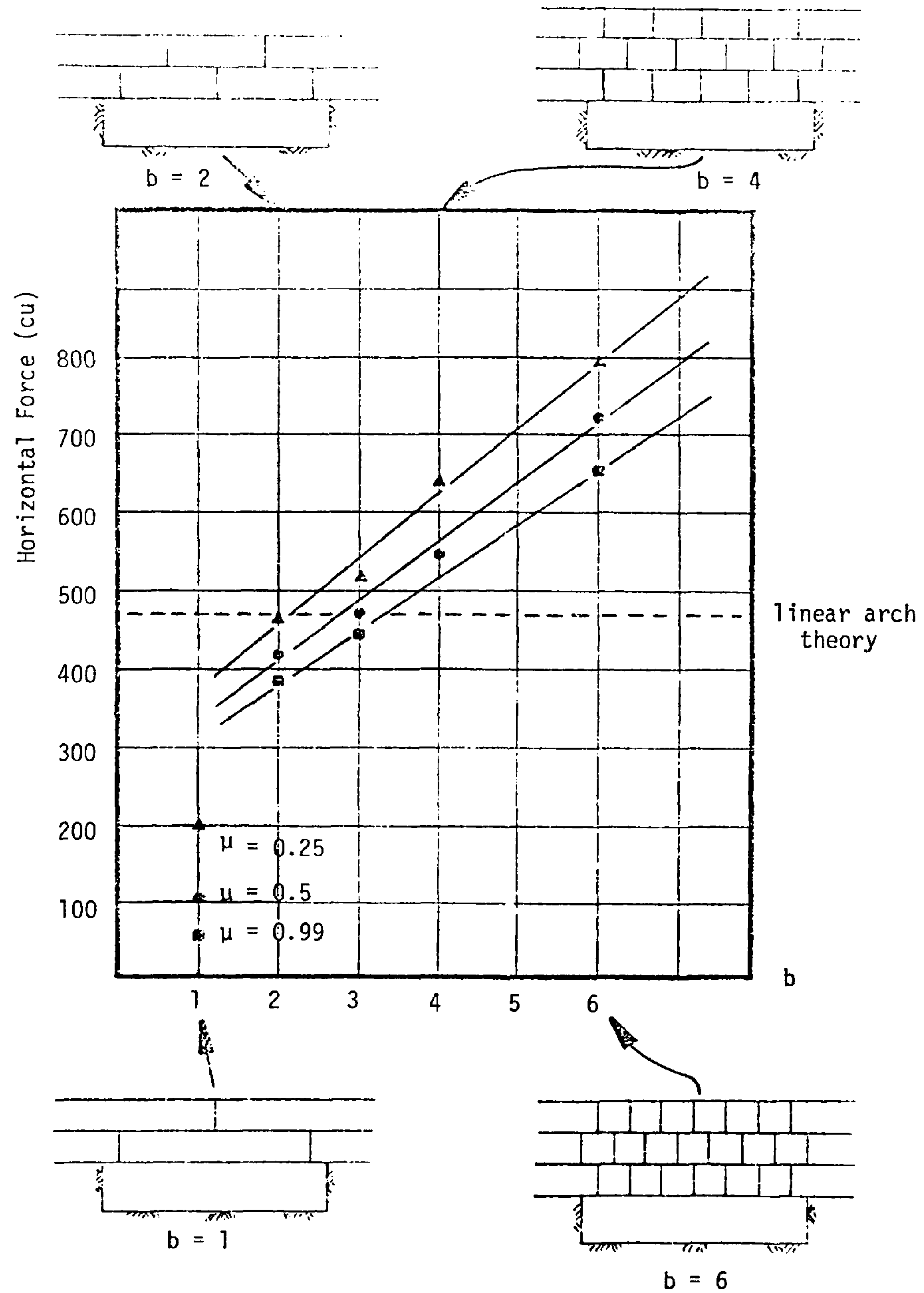
## 4.6 Use of Results in Design

The results from the previous Distinct Element runs can be expressed in a way that may be useful for design purposes. The two examples presented below utilize the data of Table 4.2 to derive empirical relationship between parameters. These relationships are characterized by errors in the order of 4% rather than the 40% error experienced when using linear arch theory to predict the horizontal thrust.

The first example derives a relationship between the horizontal force required for stability, the number of blocks in the bottom row, (a factor which is analogous to joint spacing) and the friction angle of the joints, in models similar to those shown in Figure 4.3. The excavation width and the block thickness are constant in this analysis. The data points, which represent the failure conditions for 11 test models, and the associated linear trends are plotted in Figure 4.29. The linear trends in the figure are members of a family of curves represented by the equation

$$H = 314.3 - 59.5 \tan\phi + (87.3 - 19.3 \tan\phi)\, b \qquad 4.11$$

with all dimensions expressed in consistent computer units. Also included in the figure is a horizontal dashed line which represents the value of horizontal force necessary to maintain roof stability as calculated by linear arch theory. The data points corresponding to a monolithic lower roof (b = 1) are included on the plot and are seen to deviate from the trend of Equation 4.11; the frictional resistance relationship (Equation 4.6) predicts these values




...re 4.29 Linear relationship between horizontal force, number of blocks in the lower row and joint friction angle (constant span and block thickness).

correctly.

For a constant span and block thickness, linear arch theory predicts that the value of horizontal thrust should be a constant and does not consider the effect of friction. The actual data indicate that a linear relationship exists between horizontal thrust, joint spacing in the roof and friction angle of the joints.

The data values indicate that the side force required for stability increases both as the joint spacing decreases and as the friction coefficient of the joints decreases.

The second example illustrates a relationship between the horizontal force required for equilibrium, the joint friction coefficient and the excavation span for models of the type illustrated in Figure 4.3. In this example the models have a constant block thickness and are characterized by a single midspan joint. The linear nature of the relationship can be observed in Figure 4.30. The linear trends plotted in the figure are members of a family of curves represented by the equation:

$$H = 190 \tan\phi - 540 + (1.59 - 0.48 \tan\phi)\, 0 \qquad 4.12$$

and fit the data with a maximum error of approximately 2%. All dimensioned quantities are in consistent computer units.

The dashed line included in the figure is the value of side load predicted by linear arch theory. The required horizontal force for stability is seen to increase with span as predicted by linear arch theory but the linear arch theory does not take account of the fact that an increase in the joint friction angle reduces the horizontal

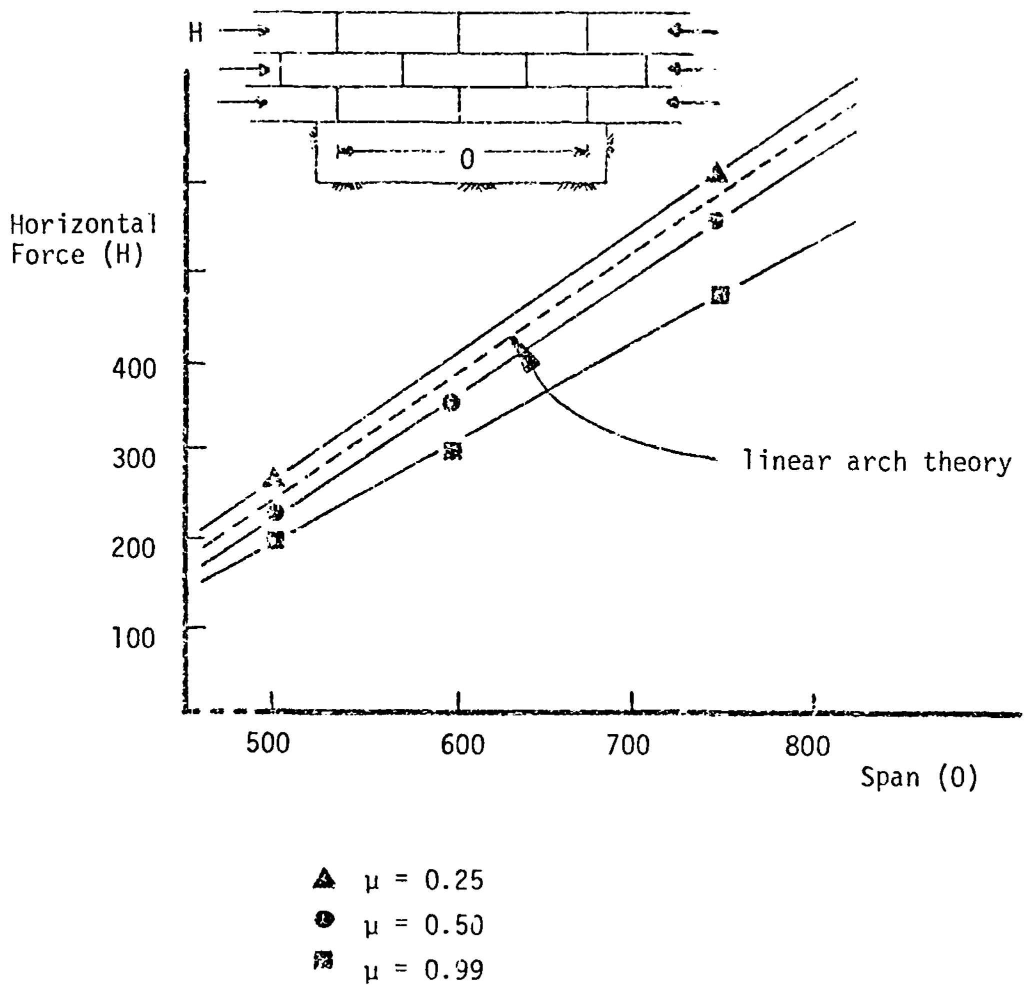



Figure 4.30 Linear relationship between span, horizontal force and joint friction angle (constant block thickness and one midspan joint; all dimensions in computer units).

load required for stability. This reduction is due primarily to the additional shearing resistance provided by the layer interactions.

## 4.7 Summary

The stability of excavations in jointed rock was seen to be governed by mechanisms of stress transfer which resulted in a zone of relatively destressed material above the excavation. This destressed zone was observed in the analyses of openings in elastic material as well in the analyses of openings in jointed masses, but the fundamental behavior was different. The elastic analyses indicated that a ground arch formed and transfered the overburden load to the abutments, but that the destressed zone was simply "hanging" on the rock comprising the arch and thus experiencing tensile stresses. The analyses of the behavior of the jointed masses indicated the formation of the ground arch as in the elastic case, but suggested that the stability of an excavation in jointed media was attained through the development of a second arch, the roof arch, in the strata immediately above the excavation. The roof arch was observed in all stable geometric configurations except for those cases involving high horizontal stresses and those cases involving large block thicknesses. In the first case the high horizontal stresses prevented the block rotations necessary to form the arches and stability was maintained by frictional suspension of the mass along the vertical joints. In the second case, the block thickness, relative to the excavation span, reached a point at which the arch development was constrained and failure of the mass was by sliding along the joints. It was found that the transition between arching and sliding behavior could be predicted accurately.

The Distinct Element obtained solutions for single layer, self loaded, jointed beams were compared to a linear arch theory neglecting the compressive strength of the rock and the lateral stiffness of the abutments; agreement of the data with theory was quite good. When the single layer, linear arch theory was compared to multiple layered models, however, agreement of the data and theory was poor. The discrepancy was seen to be due to layer interactions, not accounted for in the single layer model, acting in a manner that increased the horizontal thrust on the abutments.

A Limit Equilibrium solution for the observed contact force distribution was calculated, but discarded since the contact vectors were seldom observed to be at fully developed frictional resistance. Instead, the data was examined in order that the significant parameters and the relationships between them could be isolated. Two main conclusions could be drawn from the data. First, there is a linear relationship between the span and the horizontal thrust required for stability of the mass. However, in contrast to linear arch theory, the models examined by the Distinct Element method indicated that this relationship involved the joint friction coefficient. This was observed to be due to interactions between the lower two layers and not a resultant of slipping along the vertical joints at the abutments.

The second identified relationship indicated that the horizontal thrust was a function of the joint spacing, expressed as the number of blocks in the lower row of strata, and the joint friction coefficient. The significance of this observation lies in the fact that linear arch theory does not account for an effect due to joint

spacing. The data indicate that as the number of blocks in the lower row of strata increases from two to six, the horizontal stress required for stability almost doubles; linear arch theory, on the other hand, predicts that this horizontal stress should be a constant value.

To keep a proper perspective, it must be noted that the analyses described in this chapter were performed with a restricted behavior model possessing infinite strength and regular jointing. More sophisticated linear arch theories account for load transfer between layers and the compressive strength of the material. The real situation in bedded roofs involves crushing of the rock which can change the length of the moment arm used to calculate the horizontal thrust in the linear arch theory. It must be concluded that it may be invalid to criticize linear arch theory or the basis of the analyses just described. The analyses do indicate, however, that mechanisms act in jointed rock that perhaps should be implemented in a comprehensive linear arch theory.

# CHAPTER V

# AN ANALYSIS OF SUPPORT REQUIREMENTS OF EXCAVATIONS IN JOINTED ROCK MASSES

## 5.1 Introduction

In a historical review of tunnel construction, Szechy (1970) states that the oldest known tunnel other than those associated with mines is, according to present knowledge, over 4000 years old. This tunnel was constructed in Babalonia during the reign of Queen Semiramis to underpass the River Euphrates. The length of this tunnel was over 1 km and it had a cross-section of 3.6 m by 4.5 m. Although built by cut and cover methods, elements of the structure demonstrated (viz. a vaulted arch for the roof) that the Babylonians possessed considerable skill in tunnel construction, most likely gained from experience in previous tunneling ventures. To fully emphasize the significance of this undertaking, Szechy notes that it wasn't until 1843 that the next subaqueous tunnel, that crossing the River Thames in London, was opened, almost 4000 years later.

Significant increases in the magnitude of the scale of projects typically undertaken in underground excavation have not been accompanied by, or for that matter, preceeded by analytical techniques capable of explaining the complex behavior of the structural system comprising the rock mass and the support system. The design of tunnel or excavation support systems are routinely guided by empirical and observational rock load prediction schemes. It is universally acknowledged that the use of these schemes results in

an overdesign, but the majority of research undertaken today seems not to be directed toward understanding the mechanisms responsible for the behavior of an excavation but toward somehow strengthening the position of the empirical methods through the acquisition of additional data. This approach has helped to identify the parameters to which support design is most sensitive, but the fact that excavation support design is highly site dependent does not obviate the need for rational methods for the prediction of support pressures.

This chapter presents the results of analyses of jointed rock masses which utilize the Distinct Element method to characterize the interaction of a jointed rock mass with a support system. The vehicle chosen to quantitatively express this interaction is a ground reaction curve. A ground reaction curve is simply a plot of the support force necessary to maintain the stability of a rock mass as a function of displacement of the rock mass. The utility of the ground reaction curve in support design is that it typically yields information about the optimum time of support emplacement as well as the magnitude of the force the supports must resist.

Previously, ground reaction curves have only been calculated by continuum based methods; the rock was assumed to be broken but the representation of the behavior was by a plastic or elastic-plastic constitutive relationship.

The Distinct Element formulation provides the research tool necessary to investigate load-deflection relationships in a medium where the deformation is controlled solely by the jointing. The ground reaction curves presented in this chapter indicate a

relationship between required support force and the geometric parameters defined by the excavation dimensions and the joint spacings. This data was also compared to predictions made by several of the empirical methods in an attempt to determine if any correlation could be found.

## 5.2 The Estimation of Rock Loads for Support Design

### 5.2.1 The concept of a ground reaction curve

As an introduction to the discussion of the various methods commonly in use to design reinforcement schemes in tunnels it is prudent to discuss a theoretical concept which provides a means to quantitatively describe the behavior of the rock mass as it is disturbed by an excavation. This concept is concerned with the interaction of the material surrounding the excavation and the support system emplaced to ensure stability. The behavior of the material is described by a ground reaction curve relating the force required to stabilize the mass to the deformation of the edge of the excavation. As an illustration of the concept, an example (Deere et al., 1969) describing a ground reaction curve for a soil mass is presented.

The basis for establishing the stress for which a tunnel lining should be designed is illustrated in Figure 5.1 where the average radial stress on a circular tunnel lining is plotted as a function of the average inward radial deformation of the tunnel wall. The point A illustrated in the figure represents the average radial stress befor excavation occurs.

If the radius of the tunnel lining were steadily decreased, the load on the tunnel lining would decrease in accordance with a relationship describing the stress-strain-time characteristics of the soil. If the soil were elastic the relationship would be linear as shown in the figure by the dashed line AE; for the more likely case that the material is inelastic, the relationship could

resemble the curve AD. This relationship is termed the ground reaction curve. The form of the ground reaction curve cannot be calculated exactly but may be approximated in several instances of practical importance on the basis of field observations coupled with theoretical investigations.

As the tunnel excavation approaches a given cross-section, the soil deforms radially toward the tunnel and axially toward the working face. By the time the working face has reached the cross-section an average radial deformation, of magnitude $u_1$ has already occurred. If the tunnel lining was placed in contact with the soil at this point in time and was capable of preventing any further deformation of the soil mass, the average stress in the lining would be B as indicated in the figure. If further inward deformation of the tunnel walls occurred before the lining was placed, say of magnitude $u_2$ illustrated in the figure, the radial stress would be C.

In reality, the tunnel lining will itself undergo a radial deformation of small magnitude before stability is obtained. The effect of deflection of the lining may be estimated by a curve of its force-displacement behavior, which can be called a support reaction curve, such as the curve F in the figure. The final load on the tunnel lining is given by the intersection of the ground reaction curve and the support reaction curve taking cognizance of the fact that a certain amount of deformation of the tunnel walls has occurred before the installation of the tunnel lining. The

final stress in the tunnel lining is thus C´ and the deflection of the lining is $u_\ell$. Note that the deflection of the tunnel wall is actually given by the sum $u_1 + u_2 + u_\ell$.

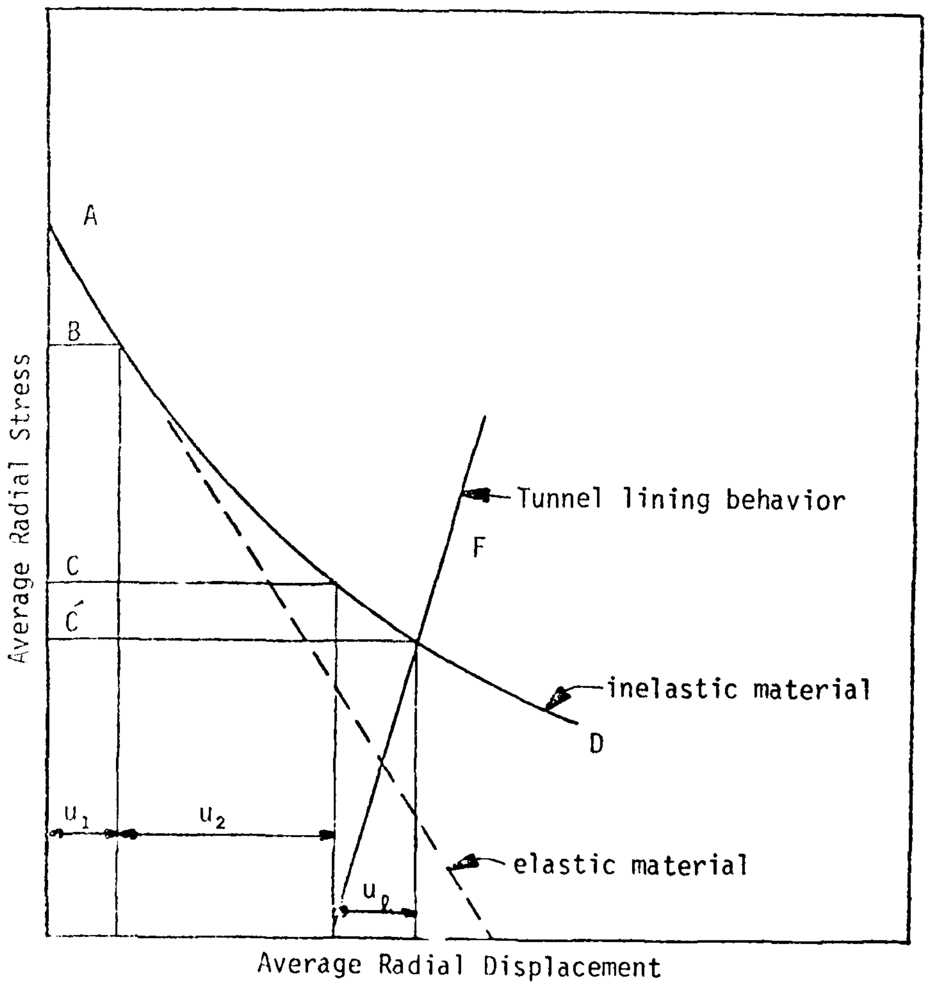



Figure 5.1 Interaction of soil and tunnel lining (after Deere et al., 1969).

5.2.2 Tunnel support design concepts

The dimensioning of tunnel supports, as with any structure, requires a fairly accurate knowledge of the magnitude of the loads to be resisted by the supports. From an economics viewpoint, it is preferable to be able to estimate support requirements on the basis of exploratory drilling footage but it is certainly acceptable to be able to modify the support design based upon observations at the working face. The fact that tunnel designers have been unsuccessful in using the first method probably explains the present trend toward instrumentation of underground construction.

This is not meant to imply that there has been a lack of proposed analytic models to explain observed rock pressure and displacement; rather the major problem with the analytic models is that they lack portability. A truly general design method would have to include all possible factors such as, mass condition, material type, construction method and type of reinforcement. Since the full implications of the many factors involved, and particularly their interactions, are not presently understood, analytical techniques are typically confined to examination of a single one of the factors. This is precisely why there are no comprehensive tunnel design-load specifications anywhere in the world and why they are compiled for each particular project on the basis of prevalent conditions.

The particular factor which is of interest in this study is the rock load for which the tunnel supports should be designed. The methods commonly in use at the present time to determine the

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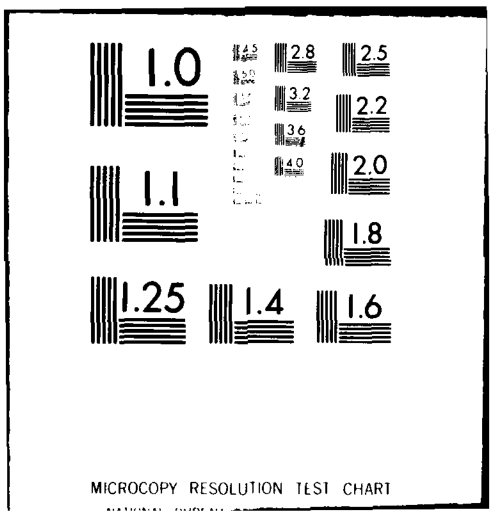


MICROCOPY RESOLUTION TEST CHART

rock pressure in the vicinity of underground excavations typically possess the characteristics of one of three categories: approximate methods based upon the extent of upbreak; theories based upon theoretical stress conditions in the rock mass; and theories based upon displacement and equilibrium assumptions. The methods which directly incorporate the jointing of the rock mass tend to be empirical rather than analytical and typically are based upon or related to the amount of upbreak above the excavation. The following brief survey of tunnel support design methods for jointed masses thus emphasizes those methods based upon the extent of upbreak. Several design concepts which do not directly include the jointing of the mass are also incorporated in the survey because they introduce concepts which are pertinent to the ensuing discussion.

The origin of the practice of dimensioning tunnel supports to resist a given amount of upbreak is usually attributed to Bierbaumer (1913), whose observations were based upon the failure of timber supports. Table 5.1 lists the values of roof pressure to be expected in various types of material. This table is frequently attributed to Bendel (1948) who actually attributes it to "others". The most significant aspect of Bierbaumer's observed rock pressure values is that they are independent of width of the excavation.

A more widely known method of estimating support loads based upon expected upbreak is that of Terzaghi (1946). Terzaghi based his estimates of the intensity of rock loads on the failure of

## Table 5.1 Observed support loads: Bierbaumer

| Rock Material | Roof Pressure $P_v$ (t/m$^2$) At out-break | Roof Pressure $P_v$ (t/m$^2$) After comple-tion of drift | Temporary timber support: Mode of execution | Temporary timber support: Degree of stressing | Remark |
|---|---|---|---|---|---|
| Rock, more or less blocky | 0 | 8-12 | Skeleton lagging, light | 0 to in-significant | Loosening pressure small |
| Very seamy rock, cemented conglomerate, soft rock, with small overburden height | 10 | 30-35 | Skeleton lagging, solid | Small | Loosening pressure increasing at the moment of outbreak not perceivable |
| Heavily fractured rock (roof breakdown), rolling gravel and conglomerate | 15-25 | 30-40 | Tight, strong lagging | Mean | Bigger pressures perceivable simultaneously with outbreak. Ensuing of equilibrium condition, very prolongated |
| Loose rock under heavy pressure (eventually in saturated condition). Bigger overburden height | 25-35 | 40-60 | Very tight, solid | Con-siderable | Stabilization of pressure conditions very difficult |
| Loose and soft (pseudo-solid) rock under heavy pressure. Very big overburden height | 40-60 | 100-150 | Very tight, lagging and strong hard-wood sill-beams | Going up to rupture | Stabilization possible only after the completion of very protracted deformations (months even years; Karawanken tunnel) |

## Table 5.2 Rock load guidelines: Terzaghi

Rock load $H_p$ in feet of rock on roof of support in tunnel

with width B (ft) and height $H_t$ (ft) at depth of more than 1.5 $(B+H_t)$

| | Rock Condition | Rock Load $H_p$ in feet | Remarks |
|---|---|---|---|
| 1. | Hard and intact | zero | Light lining, required only if spalling |
| 2. | Hard stratified or schistose | 0 to 0.5B | Light support. |
| 3. | Massive, moderately jointed | 0 to 0.25B | Load may change erratically from point to point. |
| 4. | Moderately blocky and seamy | 0.25B to 0.35 $(B+H_t)$ | No side pressure. |
| 5. | Very blocky and seamy | (0.35 to 1.10) $(B+H_t)$ | Little or no side pressure. |
| 6. | Completely crushed but chemically intact | 1.10 $(B+H_t)$ | Considerable side pressure. Softening effect of seepage towards bottom of tunnel requires either continuous support for lower ends of ribs or circular ribs. |
| 7. | Squeezing rock, moderate depth | (1.10 to 2.10) $(B+H_t)$ | Heavy side pressure, invert struts required. Circular ribs are recommended. |
| 8. | Squeezing rock, great depth | (2.10 to 4.50) $(B+H_t)$ | |
| 9. | Swelling rock | Up to 250 ft. irrespective of value of $(B+H_t)$ | Circular ribs required. In extreme cases use yielding support. |

wooden blocks of known strength inserted between the individual members of timber sets. The Terzaghi load estimates are summarized in Table 5.2. Note that the magnitude of the loads are dependent upon the tunnel dimensions as well as the presence or absence of groundwater.

Stini (1950) also presented estimates of the rock load due to upbreak which are presented in Table 5.3. Like Terzaghi, Stini's loads are dependent upon tunnel geometry, but whereas Terzaghi described the time lag between excavation and final load (bridge-action period) as typically of the same order of magnitude as the excavation cycle time, Stini noted that much longer time periods elapsed before full loads came on the supports.

Modifications of Terzaghi's basic classification scheme are frequently found in the literature and attest to its one time high degree of acceptance. For example, a report by the California Department of Water Resources (ENR, 1959) details cost data for 99 tunnels designed by a slightly modified version of Terzaghi's basic design loads.

A major effort to add a quantifying descriptor to Terzaghi's rock load classification is due to Deere et al. (1969) and Deere et al. (1970). The pertinent data from Deere et al. (1969) is summarized in Table 5.3. An easily measured field index properly, R.Q.D. is correlated to both Terzaghi's and Stini's classification scheme. This correlation provided the means to "objectively" select the proper load class.

Table 5.3 Rock Loads and Classification

| FRACTURE SPACING (FT-IN) | RQD | TERZAGHI (1946) CLASS | ROCK LOAD $H_p$ INITIAL | ROCK LOAD $H_p$ FINAL | REMARKS | STINI (1950) CLASS | ROCK LOAD $H_p$ METERS | REMARKS |
|---|---|---|---|---|---|---|---|---|
| 2' | 98 | 1 HARD AND INTACT | 0 | 0 | LINING ONLY IF SPALLING OR POPPING | 1 STABLE | 0.25+.05 B | VERY LITTLE LOOSENING |
| | 95 | 2 HARD STRATIFIED OR SHISTOSE | 0 | 0.25 B | SPALLING COMMON | | | |
| 1' | 90 | 3 MASSIVE MODERATELY JOINTED | 0 | 0.5 B | SIDE PRESSURE IF STRATA INCLINED, SOME SPALLING | 2 NEARLY STABLE | 0.50+.10 B | FEW ROCK FALLS FROM LOOSENING WITH TIME |
| | | | | | | 3 LIGHTLY BROKEN | 1.0 +.20 B | LOOSENING WITH TIME |
| 6" | 75 | 4 MODERATELY BLOCKY AND SEAMY | 0 | 0.25 B TO 0.35 C | | 4 MEDIUM BROKEN | 2.0 +.40 B | IMMEDIATELY STABLE, BREAK-UP AFTER FEW MONTHS |
| 4" | 50 | 5 VERY BLOCKY AND SEAMY, AND SHATTERED | 0 TO 0.6 C | 0.35 C TO 1.1 C | LITTLE OR NO SIDE PRESSURE | 5 BROKEN | 5.0 +1.0 B | IMMEDIATELY FAIRLY STABLE, LATER RAPID BREAK UP |
| 2" | 25, 10 | 6 COMPLETELY CRUSHED | | 1.1 C | CONSIDERABLE SIDE PRESSURE. IF SEEPAGE CONTINUOUS SUPPORT | 6 VERY BROKEN | 7.5 +1.5 B | LOOSENS DURING EXCAVATION, LOCAL ROOF FALLS |
| 1" | 2 | 7 GRAVEL AND SAND | 0.54 C TO 1.2 C | 0.62 C TO 1.38 C | DENSE | AFTER DEERE ET AL., (1969) | | |
| | | | 0.94 C TO 1.2 C | 1.08 C TO 1.38 C | LOOSE | | | |

For rock classes 4-7 when above ground water level reduce loads by 50%

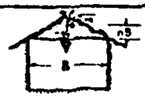
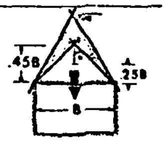
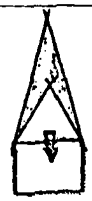
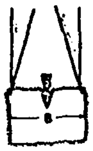
B is tunnel width, C is width + height of tunnel

The effect of jointing and faulting on tunnel support loads was emphasized by Cording et al. (1971) and Cording and Deere (1972). They noted that triangular wedges could form above the crown due to adverse joint orientation and attempted to calculate the required support pressure as a function of shearing resistance along the sides of the wedge. Later work by Cording and Mahar (1974) noted that the kinematics of the situation dictated that at least one surface of the wedge should separate from the rock mass. The equivalent rock loads they presented, which are summarized in Table 5.4, do not assume any shearing resistance in the mass but are simply the pressure due to the total weight of the wedge.

The practice of designing tunnel supports on the basis of the amount of upbreak assumes that the rock has no inherent strength and that there is no real interaction between the support and the failing mass. One recent trend in tunnel support design focuses on methods which take advantage of the strength of the mass and which incorporate mass/support interaction. The brief survey of recent work is presented only to enumerate these concepts.

The "New Austrian Tunnelling Method" described by Rabcewicz (1964) is a relatively recent construction technique for minimizing the loads on tunnel supports. In the method, a thin layer of shotcrete is applied to the tunnel walls as soon as is possible following excavation in order to prevent degradation of the rock mass and thus maintain its strength. However, as Wagner (1970) has noted, the proper use of the method requires detailed knowledge of

Table 5.4  Rock loads due to crown wedges

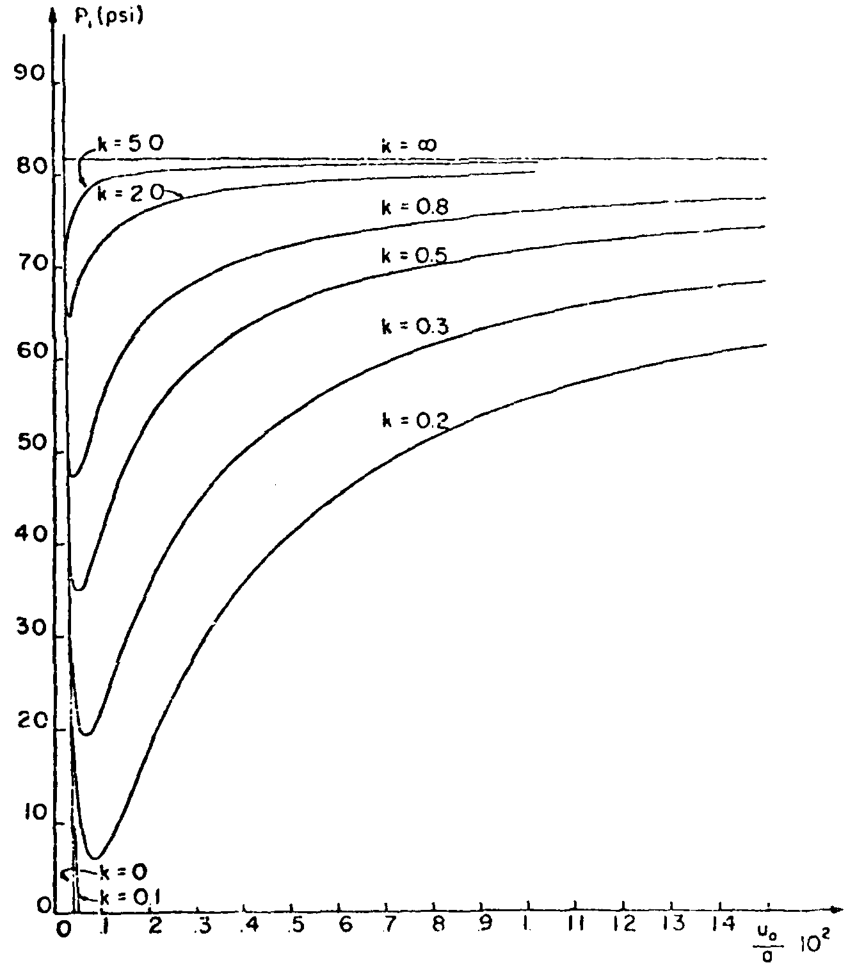
| (α) DIP ANGLE | (θ) HALF ANGLE | (nB) HEIGHT of EQUIVALENT ROCK LOAD | MINIMUM CONDITION FOR FAILURE | |
|---|---|---|---|---|
| 0° - 30° | 90°-60° | (0 - .15)B | Both planes wavy, offset |  |
| 30° - 45° | 60°-45° | (.15 - .25)B | One plane wavy or offset; One plane smooth to slightly wavy |  |
| 45° - 60° | 45°-30° | (.25 - .45)B | One plane sheared, continuous and planar, One plane slightly wavy |  |
| 60° - 75° | 30°-15° | (.45 - 1.0)B | Both planes sheared, continuous and planar |  |
| 75° - 90° | 15° - 0° | > 1.0B | Low lateral stresses in arch; Surfaces planar, smooth, possibly open, or progressive failure aided by separation along low angle joints |  |

From Cording and Mahar (1974)

the rock properties and behavior.

Daemen, Fairhurst and Starfield (1969), Daemen and Fairhurst (1973) and Daemen (1977) stress the need to consider both the complete force/deformation behavior of the rock mass and the interaction of the support system with the surrounding rock mass. Daemen (1977) presents ground reaction curves based upon a continuum analysis of an excavation surrounded by a zone of broken material possessing a residual strength. The method employed involved the determination of the pressure to be applied against the excavation surface to achieve stability; one resultant curve, typifying a material with low residual strength, is presented in Figure 5.2. This figure contains several interesting features. The line labeled $k = \infty$ represents a material characterized by a sudden loss of strength after the peak strength is reached; note that the implication of this type of behavior is that support pressure is independent of mass deformation. This is analagous to the "dead weight" loading characteristic of the design methods based upon amount of upbreak. A second interesting feature of the figure is the two lines, labeled $k = 0$ and $k = 0.1$, corresponding to materials exhibiting perfectly plastic post peak behavior. The implication of this type of behavior is that the ground will stand unsupported; in a 15 foot diameter tunnel the strain at the cessation of deformation corresponds to a displacement of approximately 0.1 inches.

Finally, the shape of the intermediate curves lends analytical support to the practice of placing the supports early. The




Note: The parameter "k" describes post peak behavior. k = 0 is a plastic post peak behavior while k = ∞ is an immediate drop to a residual strength in the post peak region.

Figure 5.2 Ground reaction curves from continuum analysis of rock with low residual strength (Daemen, 1977).

application of shotcrete immediately after excavation allows the support/mass system to equilibrate at the minimum point of the ground reaction curve.

A similar approach, presented by Panek, Dixon and Mahtab (1975), was based upon a Finite Element analysis and included the effect of joint orientation. Their work indicated that the support pressure was more sensitive to joint orientation and joint slippage than to failure of the intact rock mass.

Dixon (1971) noted the importance of including the confining influence of the rock mass on the supports and produced a Finite Element model of the support system which was iteratively used to determine the forces in the support system. The forces were the resultant of the application of independently obtained active loads and the passive resistance of the rock mass. Orenstein (1973) adopted a similar procedure using a frame model loaded by independently obtained active loads. The passive resistance of the rock mass was modeled as a spring at each blocking point characterized by a support modulus. Neither of these approaches truly models the interaction of a rock mass and its support system since the input parameters are determined independently. Typical of the methods that do model the interaction of the mass and support is that of Daemen (1975). With this model Daemen studied the progressive development of failing material surrounding an excavation and effects of support variation. His conclusions, however, stress the need for instrumentation programs to verify this type of calculation.

The other recent trend in tunneling practice has been to collect design data from actual projects, isolate common features of the design, and attempt to categorize this data by statistical manipulation so that it can be extrapolated and used for design of new projects. The attractiveness of this method in terms of the present study is that jointing of the rock mass plays a central role in all of these classification schemes.

Abel (1966) combined geologic mapping of the Straight Creek tunnel pilot bore with a limited number of support load measurements to produce a set of design charts for prediction of rock load elsewhere in the tunnel. The method was judged to be successful but Abel noted that the results might not be applicable in other locations.

A classification scheme described by Kruse, et al. (1970) related the design of pressure tunnels to the different types and quality of rock encountered during excavation. In this particular application qualitative visual criteria were related to the deformation modulus of the rock mass. Abel's (1966) classification was adopted but the authors stressed that the usefulness of a classification scheme depended upon unambiguous definition of the input parameters.

Wickham, Tiedemann and Skinner (1972, 1974), Bieniawski (1973), and Barton, Lien and Lunde (1974) present conceptually similar classification schemes for aid in the selection of tunnel supports. The classification systems are based upon (respectively): general area geology, joint orientation and spacing, and ground water and joint condition; RQD, weathering, strength, joint spacing and

orientation, joint separation, joint continuity, and ground water; and, RQD, number of joint sets, joint roughness and alteration, ground water and adverse stress conditions. All of the classification systems are relatively simple to use, utilizing data that should be routinely collected during pre-construction investigations. The methods give similar answers and can, in fact be correllated to one another (Bieniawski, 1976).

At this time it is prudent to summarize briefly those portions of the preceeding discussion which are particularly significant with respect to the present study. The majority of the methods commonly used to design support systems in jointed rock are based upon the observation of isolated failures and the extrapolation of successfully designed support systems. There is certainly nothing wrong with extrapolating previous design data to proposed ventures provided that the basic behavior mechanisms of the rock mass and support system are similar. The most significant objections to this approach are that overly conservative designs could easily propagate and that extrapolation requires a complete understanding of the pertinent geologic properties, the mass behavior, and the function of the support system.

Analytic models of the rock mass and support system provide results that indicate that the interaction of the mass and support is a significant parameter relative to the final equilibrium state. It must certainly be proper to utilize a continuum approach to study a highly stressed situation where the rock mass is failing uniformly, but there is no real evidence to suggest that this

particular representation is valid for lower stressed situations where the primary deformation takes place along pre-existing discontinuity planes. In fact, the continuum analyses that have incorporated jointing in the mass indicate that the support load is more sensitive to slippage along the joint planes than to the failure of the intact mass.

The present trend of extrapolation based upon qualitatively observed parameters and instrumentation provides a useful and practical approach to the problem of tunnel support design. However, the use of these classification schemes should be guided by rationally applied analytic models wherever possible. It is precisely in this context that the Distinct Element method is used in the remainder of this chapter. In particular, ground reaction curves are presented for several realistic models in an attempt to provide a guiding rationale for the continued use of the classification schemes.

### 5.2.3 Calculation of the potential ultimate roof loads in the jointed mass model

The discussion presented in Chapter 4.3 introduced a simple model for the behavior of the roofs of rooms excavated in a medium where the jointing was assumed to delineate blocks of a constant aspect ratio. The orientation of the joint planes was limited to either horizontal or vertical; additionally, the jointing in the vertical direction was assumed to be discontinuous. Subject to these restrictions, it is possible to describe a particular

excavation/joint configuration in terms of three geometric parameters: the true span (O); the aspect ratio of the blocks (block thickness (t) divided by block width (w)); and the height of the triangular zone (h) which delineates that material for which unrestricted movement into the excavation is kinematically possible. These geometric parameters are noted on the diagramatic section of an excavation in a jointed mass illustrated in Figure 5.3(a). The volume of material which kinematically can undergo a finite, as opposed to an infinitesimal, displacement into the excavation is outlined and indicated in the figure.

As noted in Chapter 4.3, the number of blocks (b) in the bottom row of the roof strata and height (h) of the zone of potential finite displacement are given respectively by:

$$b = O/w \quad \text{and} \quad h = b \cdot t \tag{5.1}$$

The geometric parameters of the model can also be used to determine the total weight of the material within the triangular zone of potential finite displacement. This quantity is of interest since it represents the maximum load on the support system if the downward displacement of the triangular zone is sufficient to cause loss of transmittal of vertical force across the boundary between the triangular zone and the overlaying strata.

The total weight (L) of material within the triangular zone is easily calculated in terms of the total number of blocks (B) comprising the zone. For a unit thickness normal to the plane of the paper and a given weight density (d), the total weight within the zone of potential finite displacement of the basic model

illustrated in Figure 5.3(a) is:

$$L = B \cdot t \cdot w \cdot d \qquad 5.2$$

The total number of blocks within the zone of potential finite displacement is related to the true span of the excavation and the block width. In fact, it is the quotient of these two parameters, the number of blocks in the bottom row, that leads to a simple expression for the total number of blocks in the triangular zone. The total number of blocks in the triangular zone is the sum of the number of blocks in each of n rows of blocks in the zone:

$$B = b + (b-1) + \ldots + (b-n+2) + (b-n+1) \qquad 5.3$$

The terms on the right side of the equal sign in equation 5.3 are the terms of an arithmetic progression

$$a_n = a_1 + (n-1)\,d \qquad 5.4$$

where $a_1$ is the first term,

$a_n$ is the nth term, and

$d$ is the common difference

The properties of the basic jointed mass model are such that:

$$a_1 = b, \qquad 5.5$$

$a_n = 1,$

$n = b$, and

$d = -1$

The total number of blocks in the triangular zone is given by the sum of the first n terms of this arithmetic progression:

$$B = \frac{b}{2}(b + 1) \qquad 5.6$$

The total weight of material within the zone of potential finite displacement is thus:

$$L = \frac{b}{2}(b + 1) \cdot t \cdot w \cdot d \qquad 5.7$$

In terms of the true span of the excavation:

$$L = \frac{0t}{2} \left(\frac{0}{w} + 1\right) d \qquad 5.8$$

Equation 5.8 was used to obtain the five sets of curves presented in Figure 5.3. Each family of curves represents a constant block width while each curve within a family represents a different block thickness. The thickness values increase in an upward direction. The calculations were performed using a weight density of 150 pcf; all length dimensions are thus in feet. Since equation 5.8 is linear with respect to density, the curves may be corrected for any desired density simply by multiplying the load by the quotient of the desired density, in pounds per cubic foot, and 150 pcf.

The graphs illustrated in Figure 5.3 should be used with caution since the model upon which they are derived is based upon integer values of the number of blocks in the lower row. Although the curves give a seemingly proper value of the load for non-integer values of b, the jointed model is only defined for those instances where the span is an integer multiple of the block width. It must also be noted that even though the complete curves have been plotted in all cases, the model is also undefined in those instances where the true span is less than the block width. This cutoff point has been indicated on the abscissa of each plot by a small triangle; the curves are not valid for the basic model to the left of this

cutoff point.

The graphs of Figure 5.3 indicate that the total weight of the triangular zone increases parabolically with span and that for a given block width and span, increasing the thickness of the blocks leads to an increased load. On the other hand, for a constant span and thickness, increasing the width of the blocks decreases the loads on the supports.

By a suitable choice of variables it is possible to plot all of the data of Figure 5.3 as a single linear relation between dimensionless variables. This plot is presented in Figure 5.4. Although this plot lacks the utility of Figure 5.3, its value is due to the fact that it is valid for any consistent set of units. For example, consider an excavation in a medium with a weight density of 26 $KN/m^3$ and jointing in the manner of the basic model leading to blocks of thickness 0.5m and width 1.5m. The aspect ratio of the blocks is thus 0.33. For an excavation 12m in width, the true span (O) is 10.5m; the number of blocks in the bottom row of the roof strata, which is the ratio O/w; is thus seven. Referring to Figure 5.4 an ordinate value 4.0 corresponds to an abscissa value 7.0. The potential ultimate load corresponding to a finite displacement of the triangular wedge can be determined by multiplying the known parameters out of the ratio. The load is thus $4 * 10.5m * 0.5m * 26\ KN/m^3$ or 546 KN per meter of excavation length.

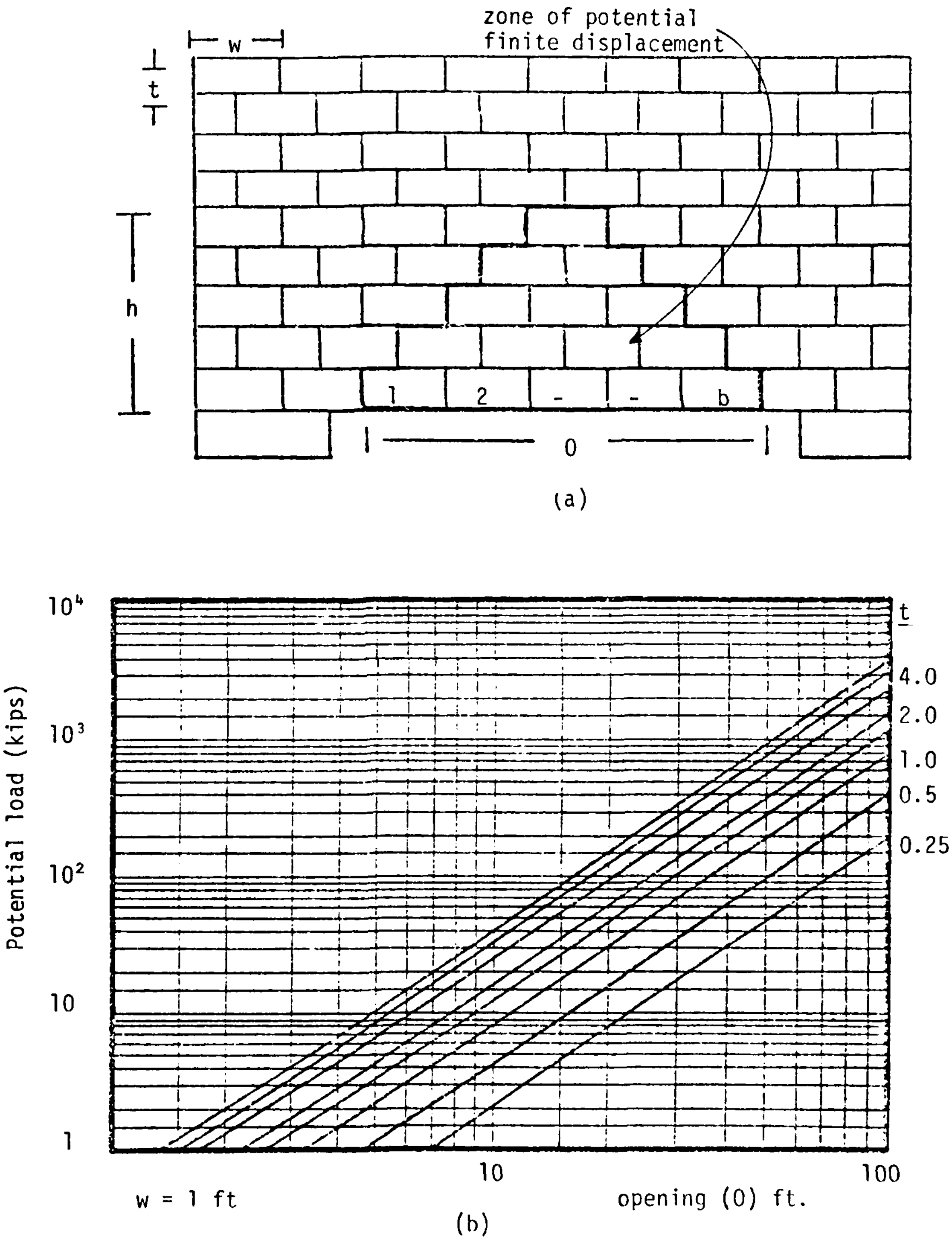



Figure 5.3 Ultimate potential load to be resisted by supports for basic jointed roof model: (a) basic model; (b) block width = 1 foot;

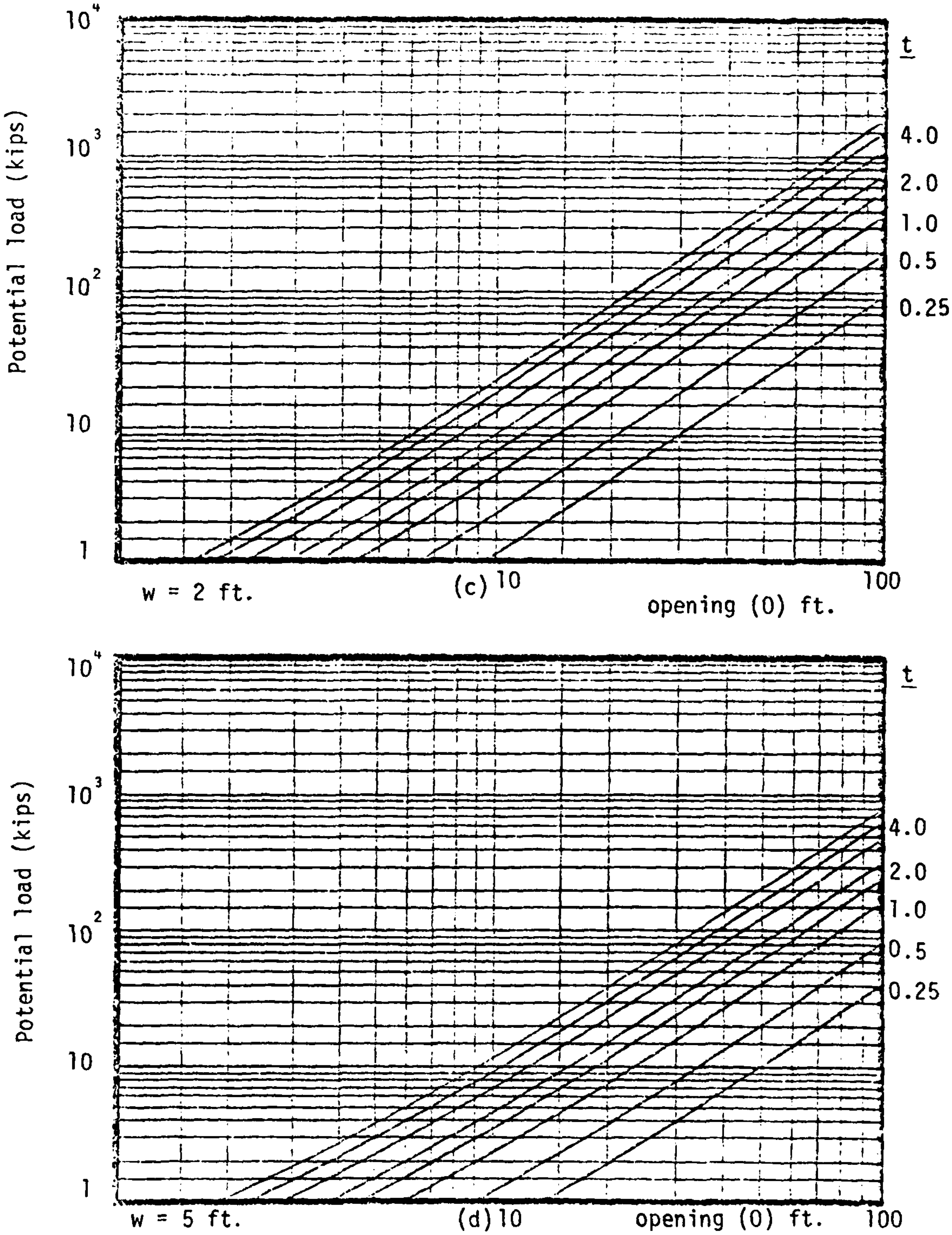
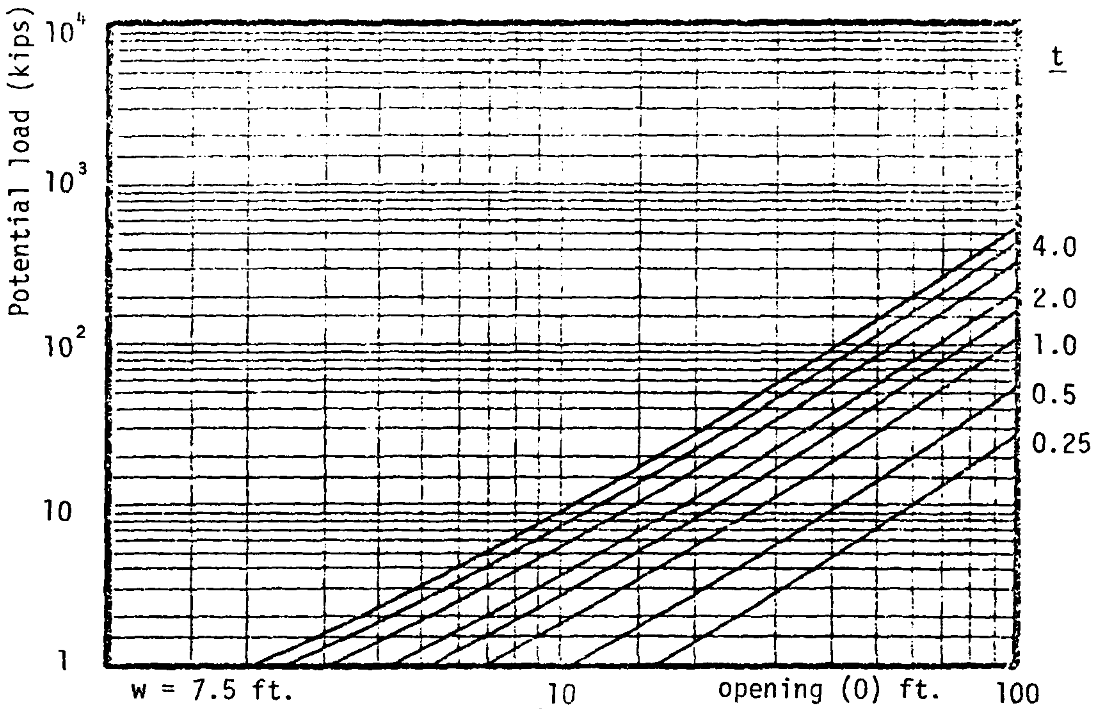
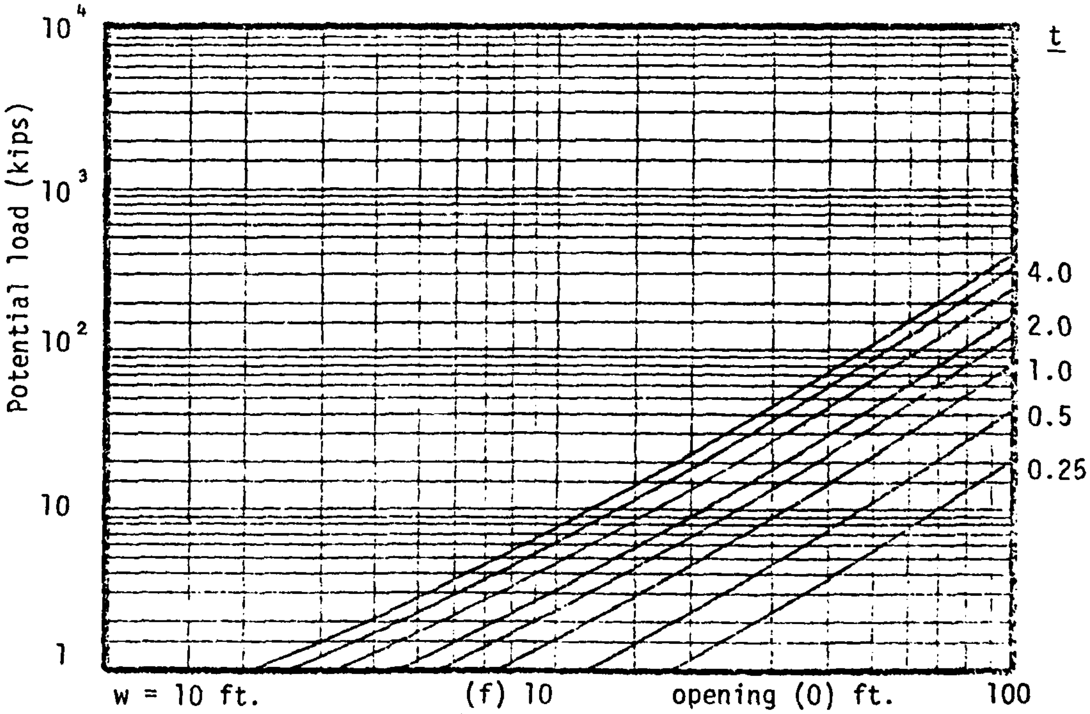



Figure 5.3 (continued) (c) block width = 2 feet; (d) block width = 5 feet;




(e)




(f)

Figure 5.3 (continued) (e) block width = 7.5 feet; (f) block width = 10 feet.

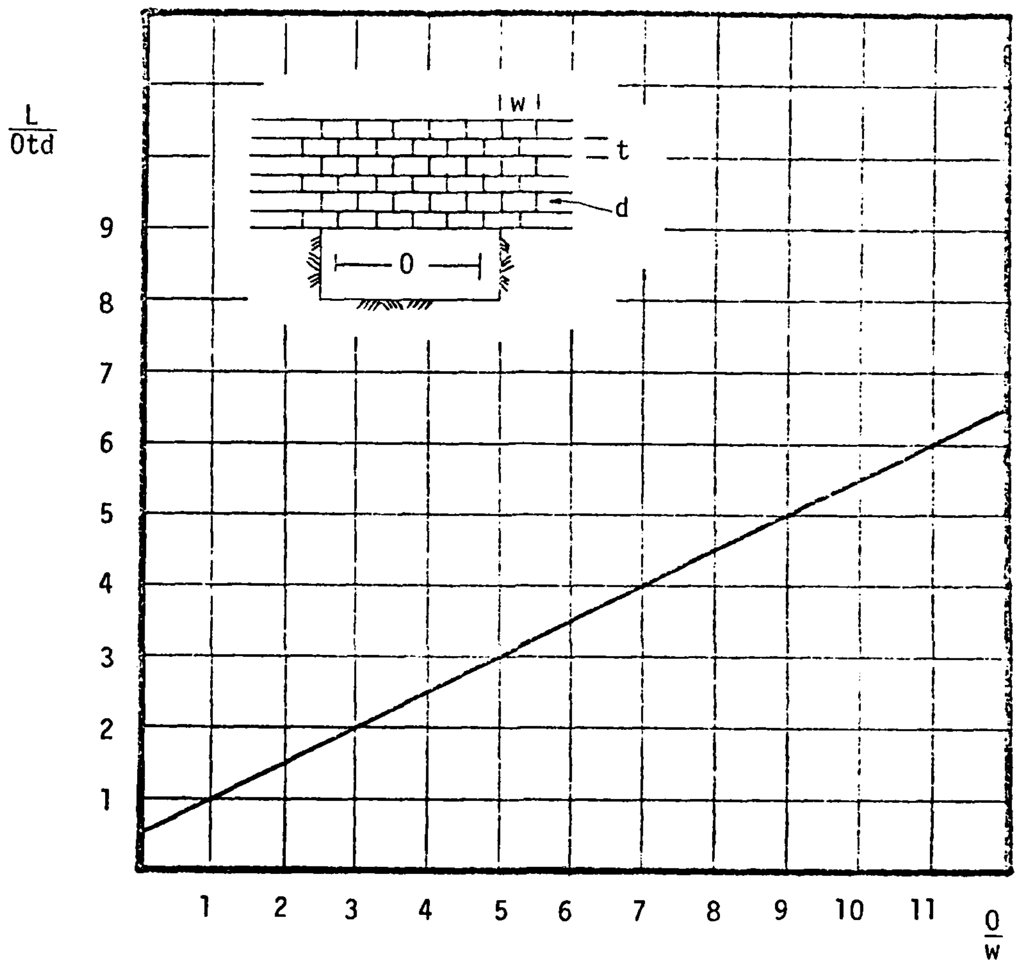



Figure 5.4 Dimirsionless linear relationship between span, block width, block thickness, density and potential ultimate load.

5.2.4 <u>The use of displacement controlled fixed blocks to generate ground reaction curves</u>

A ground reaction curve is a particular example of the non-linear stiffness behavior of a jointed rock mass which can only be determined in reality by a succession of measurements. These measurements reflect the changing relationship between the load to be resisted by the supports and the inward displacement of the rock mass. Since the force sum acting on a spatially fixed block is automatically calculated by the Distinct Element program, a spatially fixed block can be utilized to determine the magnitude of the support force necessary to stabilize a failing rock mass. A value so determined is of use because it is a point on the ground reaction curve but this information is of much more value if the complete ground reaction curve can be determined.

The solution to the problem of determining a complete ground reaction curve by the Distinct Element method requires that some type of automated control mechanism be incorporated in the model to vary the position of the load indicating block.

Analogous to a laboratory testing frame, there are two basic governing control mechanisms: force control, which requires a freely moving block; and displacement control which requires a spatially fixed block. Both mechanisms require that a small block be placed against the strata in the manner illustrated in Figure 5.5(a) and (b).

To implement the force controlled testing machine, the force

on the load indicating block is reduced by some amount. The net result of this action would be an acceleration, due to the excess load imposed by the strata, of the load indicating block away from the strata, continuing until equilibrium of the system was again achieved. In practice, there are two serious drawbacks to the implementation of a force controlled testing machine. The first problem is concerned with inertial effects. Beginning at point (1) on the ground reaction curve illustrated in Figure 5.5(c), a force reduction of magnitude $\Delta F$ should again reach equilibrium at point (2); however, the inertia of the system could cause the jointed mass to temporarily experience the conditions at point (3). Since the applied force is higher than that required for equilibrium, the load indicating block will move toward the strata. Owing to the highly non-linear stiffness behavior of a jointed mass, it is likely that this reloading will follow a different behavior curve than the unloading curve. In the case illustrated, the reloading curve is stiffer than the loading curve, and the mass comes to equilibrium at point (4) instead of point (2). The result of this is that instead of the true ground reaction curve (1) - (2) - (3), the data would indicate curve (1) - (4) as being the ground reaction curve.

The second problem that would be encountered would occur if the ground reaction curve had an upswing such as the segment of the curve (6) - (7) in Figure 5.5(c). The postulated force controlled testing machine would continue to lower the force applied

to the load indicating block and thus, equilibrium could not be reached.

A displacement controlled governing mechanism is not foolproof either. Although not subject to the inertial effects of the freely moving block utilized in the force controlled testing machine, the displacement control of a fixed block can also lead to incorrect results. One point of interest, which is addressed later in this chapter concerns the interaction of the support and the rock mass. If the presence of a support force affects the development of arching within the rock mass, then a large displacement step could pull the support away from the rock mass and all interaction between the support and the rock mass would cease. One consequence of this type of action is illustrated in Figure 5.5(d). If, indeed, arching does occur and stabilize the rock mass so that the generated ground reaction curve is (1) - (2) - (3) - (8) as illustrated in the figure, the displacement steps must be small enough so that the support-mass interactions are faithfully modeled. It is possible that the presence of the support tends to inhibit roof arch development; if this is indeed the case, then the true ground reaction curve would be (1) - (2) - (3) - (6) - (9). This problem will not arise if the displacement steps are small enough.

It might be noted that the mechanism of unfixing a block and letting it move to a new position before refixing it does not lead to an acceptable solution. The force sum acting on the fixed block is a large quantity relative to the weight of the fixed block. Thus when the fixity of the block is removed, high acceleration would

tend to make the now free block undergo a large displacement. This of course, could lead to the same problem illustrated in Figure 5.5(d).

The actual mechanism incorporated in the Distinct Element program is the displacement controlled fixed block. The routine modifies the low order (high precision) part of the fixed block centroid coordinates. Displacements in the x coordinate direction and the y coordinate direction are specified as well as the number of cycles between displacement steps. Once the displacement control mechanism is enabled, it will continue to incrementally move the load indicating block, until the control mechanism is disabled. In this manner, the displacement control mechanism functions as a testing machine with the output being a ground reaction curve for the rock mass in question. In actual use, however, the mechanism is disabled at frequent intervals to ensure that the mass/support system reaches equilibrium before continuing the displacement of the load indicating block.

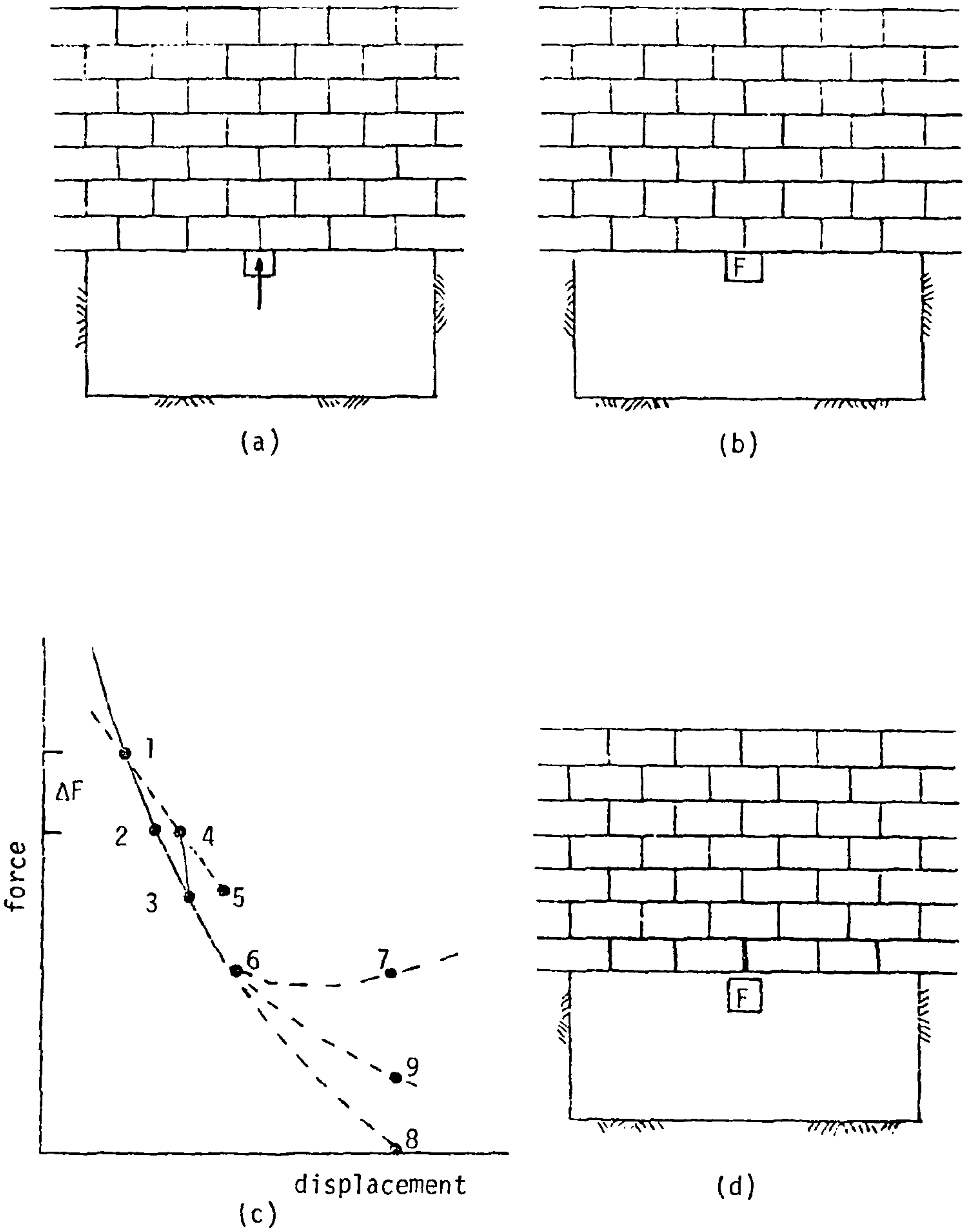



Figure 5.5 Mechanisms for obtaining ground reaction curves for jointed rock mass (a, b and d) and generalized force displacement curve (c).

## 5.3 Support Requirements in the Absence of Arch Development

In order that the development of the ideas presented in this chapter be complete, it is prudent to examine the support requirements for the simple monolithic roof model presented in Chapter 4.4. Recall that owing to the absence of flexural deformation in the model, arching behavior was unable to develop and stability of the single block was achieved by frictional resistance acting along the vertical joints. For those situations where the magnitude of the horizontal force acting on the block is insufficient to prevent failure of the roof through downward movement of the block, equilibrium, and thus the integrety of the roof, can only be obtained by the application of an external force.

The Limit Equilibrium models utilized in Chapter 4 can easily be modified to incorporate an external force or the resultant of an external support pressure; the modified models are illustrated in Figure 5.6(a). The assumptions of symmetry of the frictional reactions and the full mobilization of frictional resistance lead to an equation of vertical equilibrium which is given by:

$$P = W - 2 \tan\phi \qquad 5.9$$

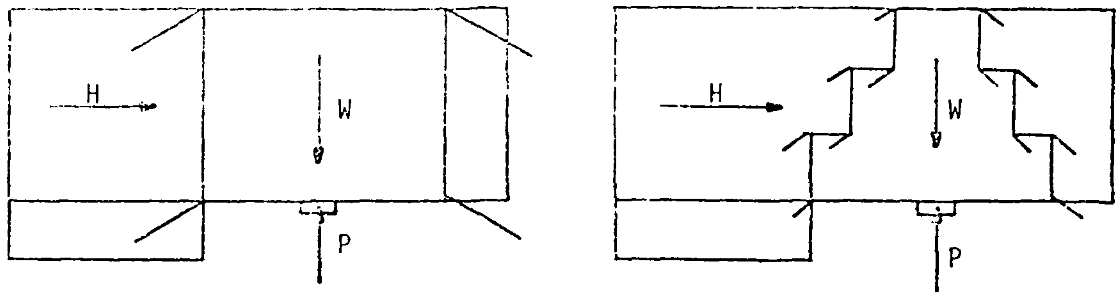
where: P is the external support load;

W is the weight of the block

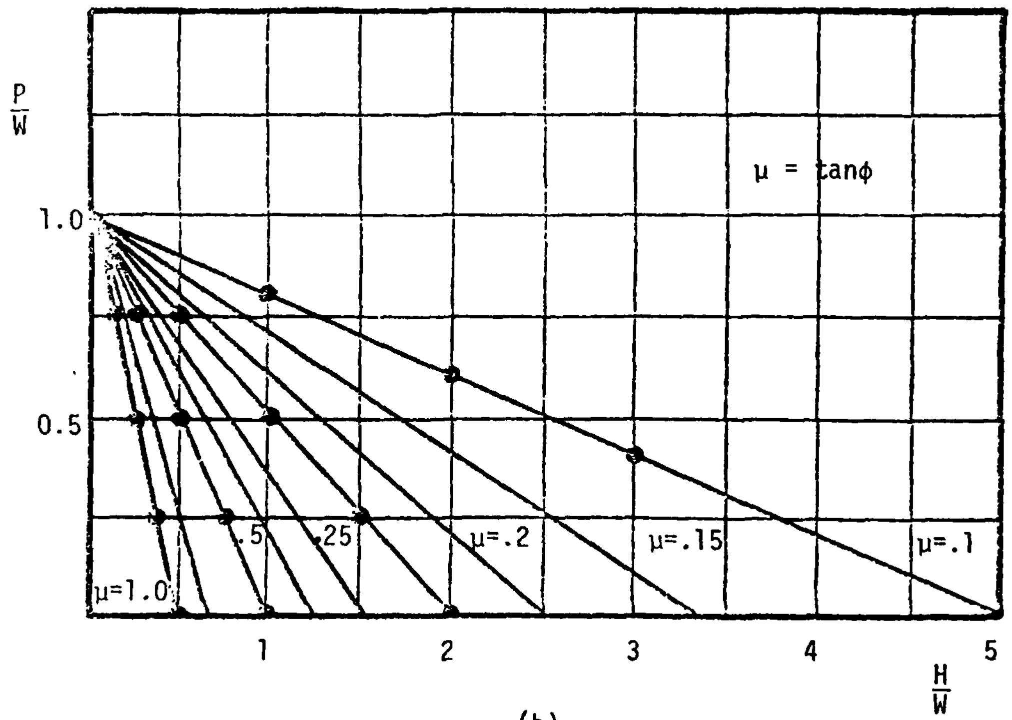
H is the total horizontal thrust; and

$\phi$ is the angle of sliding friction of the joints.

If the support load and horizontal thrust are normalized with respect to the weight, a diminsionless form of equation 5.9,




(a)




(b)

Figure 5.6 (a) Limit Equilibrium models of roof behavior under combined frictional suspension and external force. (b) external support requirement for stability of frictionally suspended roofs.

$$\frac{P}{W} = 1 - \frac{2H}{W}\tan\phi \qquad 5.10$$

is obtained. This equation is plotted in Figure 5.6(b) for various values of $\tan\phi$. As was expected, the magnitude of the external support force decreases with increasing horizontal thrust; the decrease is more rapid for higher joint friction angles.

A number of unstable, monolithic roof geometries were modeled using the Distinct Element method for purposes of comparison to equation 5.10. In these models the external support load required for stability was either applied to the centroid of the roof block or applied to the centroid of a small block placed at midspan on the bottom of the roof block specifically for this purpose. There was no discernable difference in the results obtained by the different methods. Examination of Figure 5.6(b) reveals a high degree of correlation between the Limit Equilibrium solution and those calculated by the Distinct Element method.

The basic model dealt with in this study forms an inverted "staircase" in the roof when failure occurs (see Chapter 4.3). The geometric relationships relating total roof load to the span of the excavation and the aspect ratio of the blocks formed by the jointing which were developed in the preceeding section can be used to determine the magnitude of the parameter W in equation 5.9. Bearing in mind the fact that the roof is monolithic it is still possible to calculate a ficticious aspect ratio for the joints that form the vertical sides of the roof block. Thus equation 5.7 or 5.8 may be used to determine the total weight of the roof. If the support

force is assumed to be some percentage (K) of the total roof load and if in addition, the total horizontal thrust (H) is expressed as the height of the arch (h) multiplied by the horizontal stress ($\sigma_h$), then K is given by the relation:

$$KW = W - 2H \tan\phi \qquad 5.11(a)$$

$$K = 1 - 2 \frac{O\frac{t}{w}\sigma_h \tan\phi}{\left(\frac{O^2 t}{2w} + \frac{Ot}{2}\right) d} \qquad 5.11(b)$$

$$K = 1 - 4R/(O + w) \qquad 5.12$$

The stress factor (R) is defined as

$$R = \frac{\sigma_h \tan\phi}{d} \qquad 5.13$$

All of the above mentioned parameters are illustrated in Figure 5.8.

Figure 5.7 illustrates the relationship between the percentage of the roof load to be supported (K), the true opening width (O), the stress factor (R) and the block width (w). The three separate graphs correspond to different values of w, chosen to represent: a high fracture frequency or a low RQD (w = 2 in.); a moderate fracture frequency or RQD (w = 10 in.) and; a low fracture frequency or a high RQD (w = 25 in.). The curves demonstrate an increase in the percentage of support required corresponding to an increase in block width; this reflects the fact that for any given block thickness, an increase in the block width tends to make the roof block assume a rectangular rather than a triangular shape. The percentage of support required also decreases with increasing horizontal stress

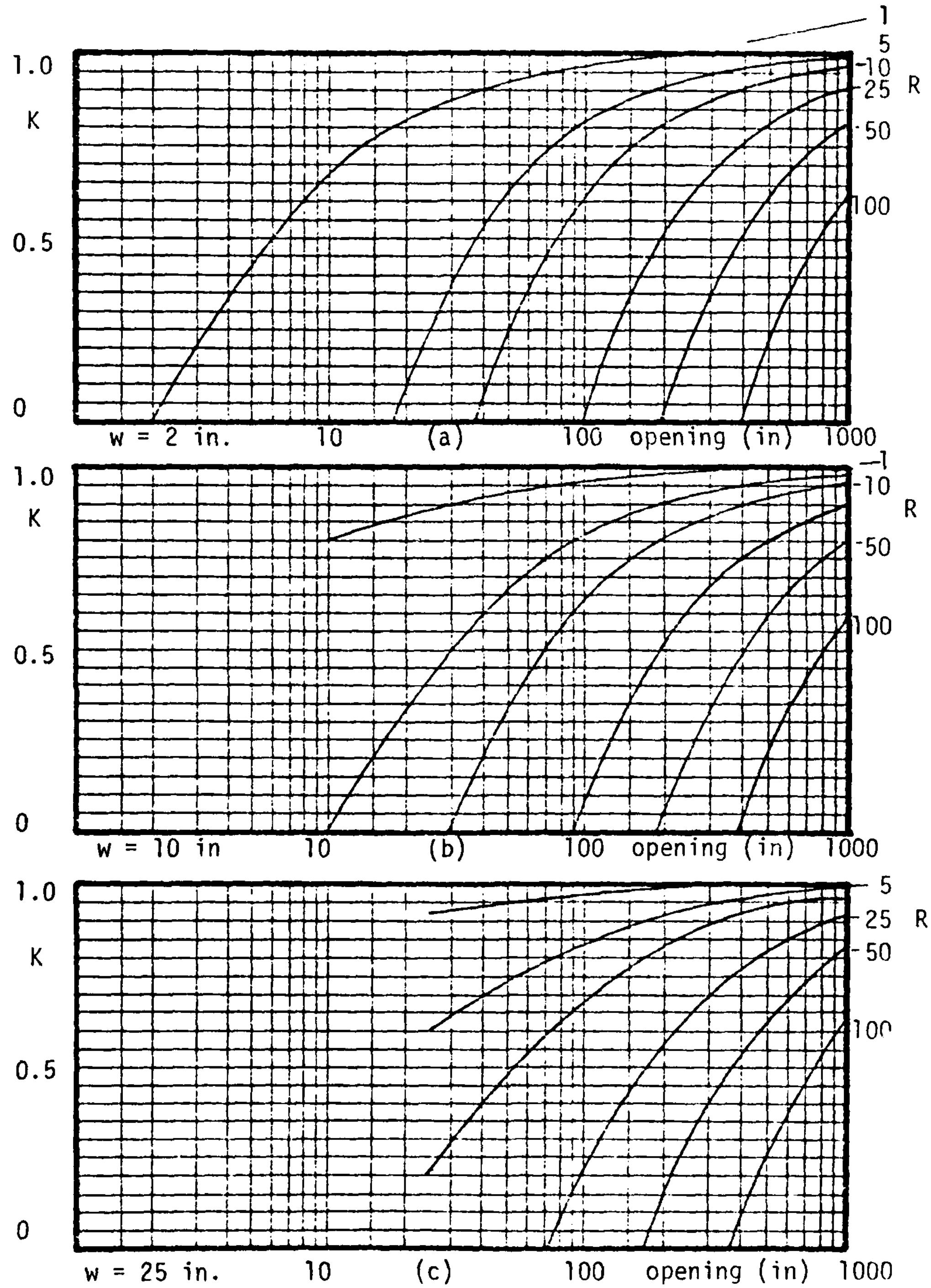



Figure 5.7 Percentage of total roof weight (k) to be supported as a function of true opening (O) for varying block width (w) and stress factor (R).

($\sigma_h$) or friction coefficient ($\tan\phi$) or decreasing material density (d). This fact is expressed by the stress factor (R) which is also incorporated in the graphs shown in Figure 5.7.

Equation 5.12 can also be used to determine the maximum unsupported span length for the model illustrated in Figure 5.8 simply by solving for the situation where there is no required external support force (K = 0). Under these stipulations, equation 5.12 becomes:

$$0 + w = 4\,\frac{\sigma_h \tan\phi}{d} \qquad 5.14$$

The quantity 0 + w is the excavation width (S) illustrated in Figure 5.8; the figure also presents a plot of excavation width (S) as a function of horizontal stress ($\sigma_h$) for different values of $\tan\phi$. This figure can be used to determine the maximum expected horizontal span for a monolithic roof failing by slipping along vertical joints in the presence of a horizontal stress field.

The model under consideration does not incorporate failure by arching but it is of interest to know if the maximum span predicted by equation 5.6 exceeds the span at which failure by arching would occur. This can be determined for the simple case of a rectangular roof comprised of two blocks, since the rigid block analyses of single layer model arching developed in Chapter 4.5.3 indicated that a clearly defined boundary between failure by sliding and failure by arching could be determined for a multi-block, single layer model. In terms of maximum unsupported spans for a two block rectangular

roof, equation 4.3 may be rewritten:

$$0 = 2 \frac{\sigma_h}{d} \tan\phi \qquad 5.15$$

Likewise, equation 4.9, which relates horizontal thrust to span may be rewritten:

$$0 = \sqrt{8 \frac{\sigma_h}{d} t} \qquad 5.16$$

It is thus possible, at least in the simple case of a roof comprised of two rectangular blocks, to determine if the calculated maximum unsupported span exceeds the approximate value of the span at which failure occurs by arching.

Equations 5.15 and 5.16 are actually tne dividing lines that separate zones of stability and instability; in the first case the equation delineates that zone where sliding will occur and in the second case, the equation delineates that zone where failure will be by arching. Equations 5.15 and 5.16 have been plotted in Figure 5.9 with horizontal stress plotted as a function of span, various values of the joint friction coefficient have resulted in a family of curves, inclined at about 25 degrees from the span axis, that delineate the zones of sliding failure. Similarly, various values of the block thickness have resulted in the family of curves, at the steeper inclination, that delineate the zones of arching failure. When plotted on the same figure, these two equations thus delineate four zones, indicative of the condition of the roof, that are dependent upon the block thickness and the joint friction

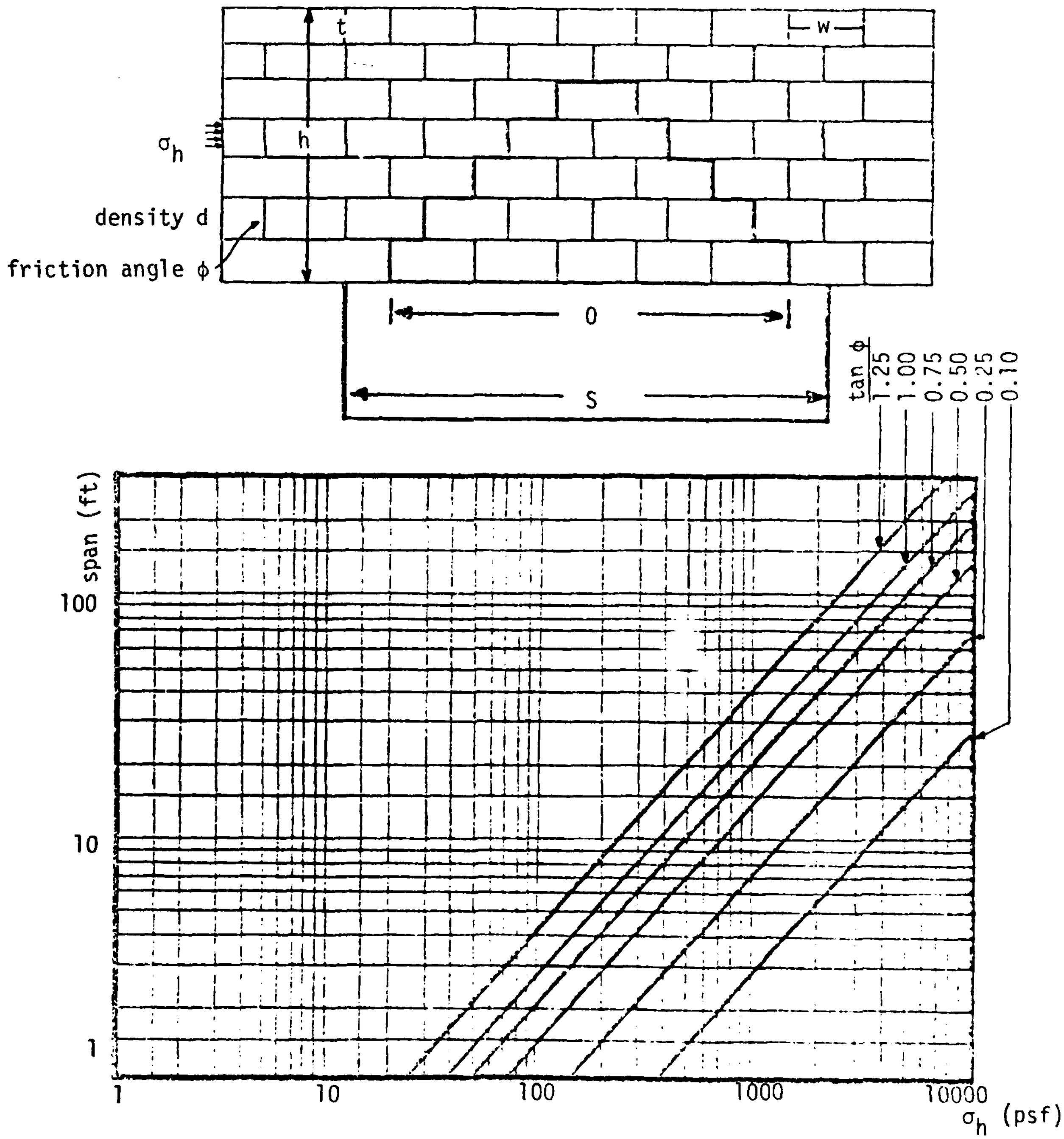
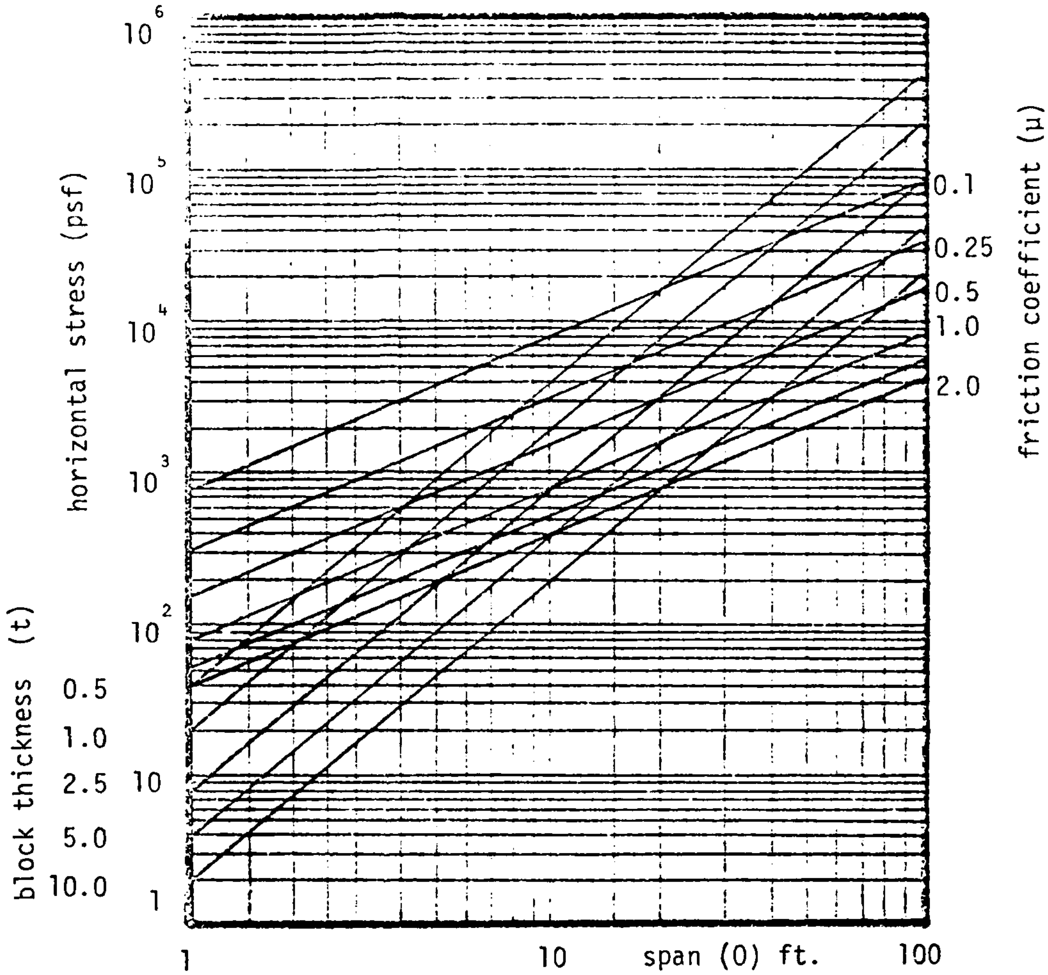



Figure 5.8 Maximum unsupported spans (S) for non-arching model as a function of horizontal stress ($\sigma_h$) and friction coefficient ($\mu_1$)

coefficient. To use Figure 5.9 the curve corresponding to the block thickness and the curve corresponding to the friction coefficient are selected. The point corresponding to the span and horizontal stress will then lie in one of four zones. The zones correspond to complete stability, failure by sliding, failure by arching, and failure by sliding and arching. These zones are illustrated in Figure 5.9 for the particular case $t = 2$ feet and $\tan\phi = 0.5$.



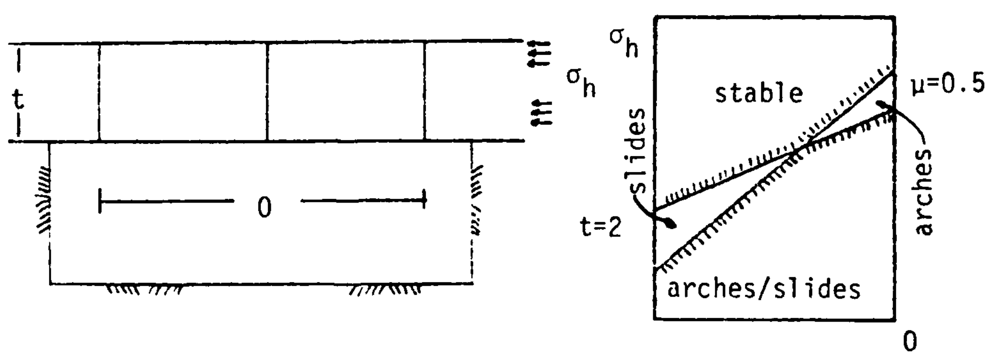




Figure 5.9 Conditions for failure by arching or sliding for the illustrated roof geometry.

## 5.4 An Investigation of Support Requirements in Jointed Roofs

### 5.4.1 Jointed mass behavior representation by means of ground reaction curves

The brief survey of design concepts presently in use to aid in the dimensioning of tunnel supports indicated that the majority of the methods that recognize the rock mass as a jointed discontinuum are of an empirical nature and are often criticized for their failure to account for the interaction of the support system and the rock mass. However, the fact that the older amount of upbreak or dead weight loading schemes (Bierbaumer, Terzaghi and Stini) are based upon observations, admittedly crude, of pressures acting on installed support systems indicates that there is at least some partial measure of the support/mass interaction incorporated within them. The same is true of the newer schemes (Wickman, Tiedeman and Skinner, Bieniawski, and Barton); the design pressures are based upon actual installed support data supplemented by instrumentation data where it was available. Thus the interaction of the mass and support system is incorporated in these schemes even though it is not somehow explicitly expressed as one of the basic input parameters.

Conspicuous in its absence, however, is analytical substantiation of the required support loads predicted by the empirical schemes for those instances where the failure of the rock mass and the resulting loading of the support system is governed by the presence of distinct planes of weakness, such as joints and

faults, within the rock mass. The Distinct Element method provides the mechanism to investigate the behavior of jointed masses which are controlled by the behavior of the joints. Additionally, the implementation of the displacement controlled testing mechanism described in Chapter 5.2.4 provides the data necessary to quantitatively describe the behavior of the jointed rock mass as it interacts with a simple support system.

The Distinct Element method has been used to study the support requirements of numerous excavation roofs which possess the joint pattern characteristic of the basic model utilized in Chapter 4. These characteristics are regular, continuous jointing in the horizontal direction and regular, discontinuous jointing in the vertical direction. Once again, this is a plane strain model and the aspect ratio of the blocks for a given problem is a constant. The results of this investigation are presented in this section by means of several ground reaction curves which are representative of the observed responses.

The results presented in Chapter 4 indicated that the stability of the roof of an excavation in jointed rock was most sensitive to the magnitude of the horizontal stress. It follows logically, therefore, that an investigation of the support requirements of excavations in jointed media should be concerned with the effect of horizontal stress on the ground behavior as expressed by a ground reaction curve relating the total load acting on the support to the vertical deflection of the support.

The models analyzed in this chapter are subject to the limitations of those described in Chapter 4, namely highly idealized joint behavior and a simplified mechanism for modeling the horizontal stress. The joints are modeled as planar and do not possess cohesion. The tendency of construction procedures such as blasting is to destroy the cohesion of the joint surfaces near the excavation. This, coupled with the fact that the models portray the behavior of failing masses leads to the conclusion that the analyses are valid in terms of the cohesive strength of the joints. The fact that the joints are considered to be planar, however, does detract somewhat from the validity of the analyses. Real joints are non-planar; perfectly mating rough surfaces can only be forced to slide relative to one another if they are free to move apart. This dilatancy leads to increased mass strength for if the joint separates two confined blocks, the only way relative movement can occur is if shearing of the rock mass takes place. As noted in Chapter 4.5.2, the horizontal stress field is modeled as a constant load, owing to the rigid nature of the blocks in the Distinct Element formulation. Under a constant load situation strength increases due to dilatancy do not occur. The analyses presented in this chapter are probably only realistic for problems where dilatancy does not play a significant role. Near surface excavations with relatively open or infilled jointing are examples of such a situation.

Figure 5.10 presents two ground reaction curves for the six

meter wide excavation illustrated in the figure. Part (a) of the figure illustrates the ground reaction curve for a case where sufficient horizontal stress exists to stabilize the mass in the absence of externally applied support. The ground reaction curve reflects this fact indicating that a value of the roof deflection of approximately five centimeters, the load acting on the supports is zero. The second ground reaction curve illustrated in the figure represents a situation where the magnitude of the horizontal stress field is insufficient to stabilize the mass without the introduction of external support. The parameter W, indicated on the ground reaction curve, is the total weight of the material within the zone of potential finite displacement described in Chapter 5.2.3. W is thus that quantity which was previously termed the potential ultimate roof load. The form of the ground reaction curve suggests that as deflection of the roof continues the required support force approaches a constant value, and that this value is given by the potential ultimate of load W.

A similar situation a four meter wide excavation where the blocks have a significantly lower aspect ratio (0.4 as opposed to 1.5 for the first case) is presented in Figure 5.11. As before, the two ground reaction curves represent the situations where sufficient stabilizing horizontal pressure is present (part a) and the case where external support is required for stability for the roof (part b). However, in this case, the ground reaction curve in the first part of the figure represents the behavior of the mass where the applied horizontal stress is

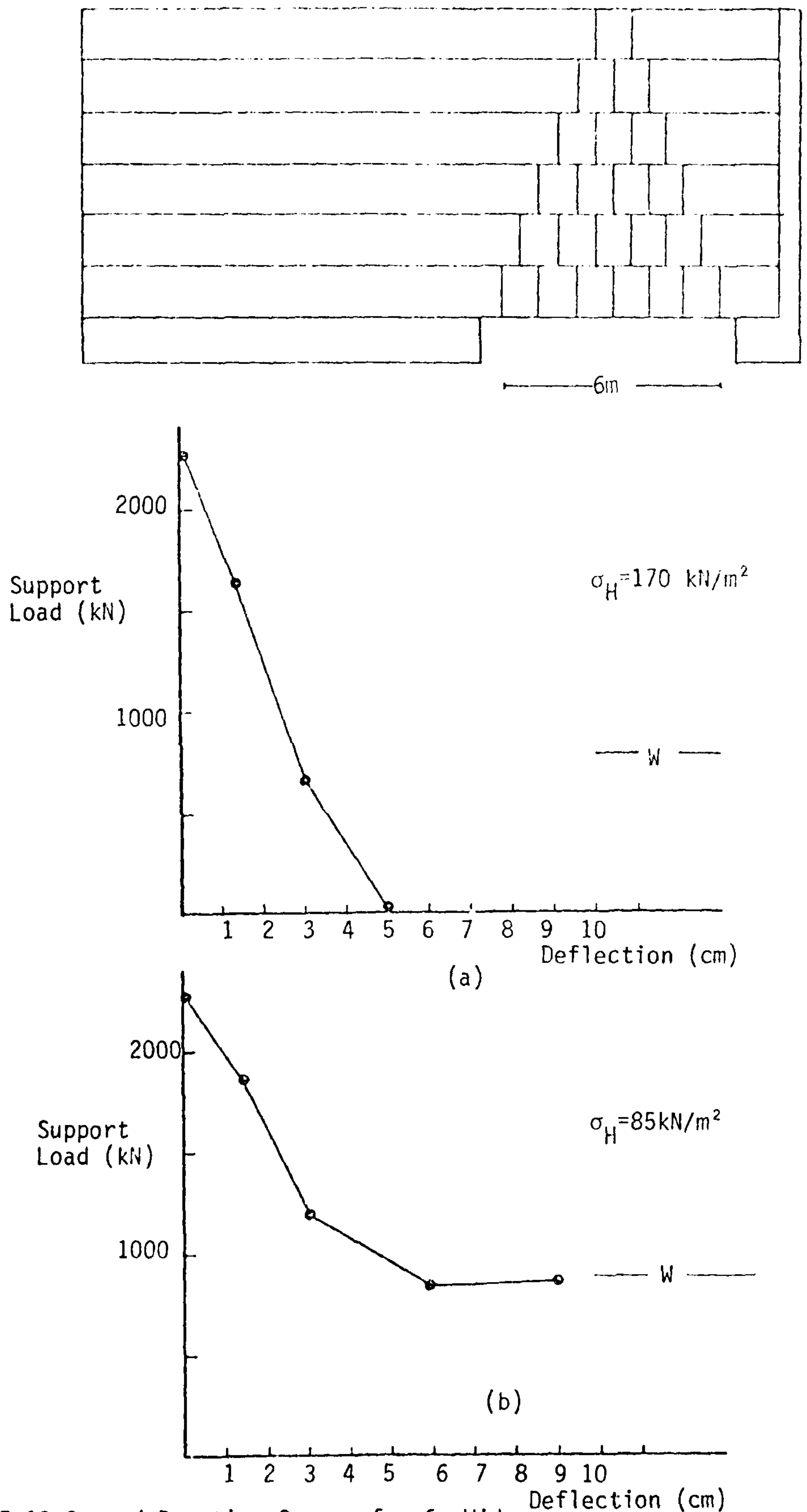



Figure 5.10 Ground Reaction Curves for 6m Wide Excavation:(a) High Horizontal Stress;(b) Low Stress.

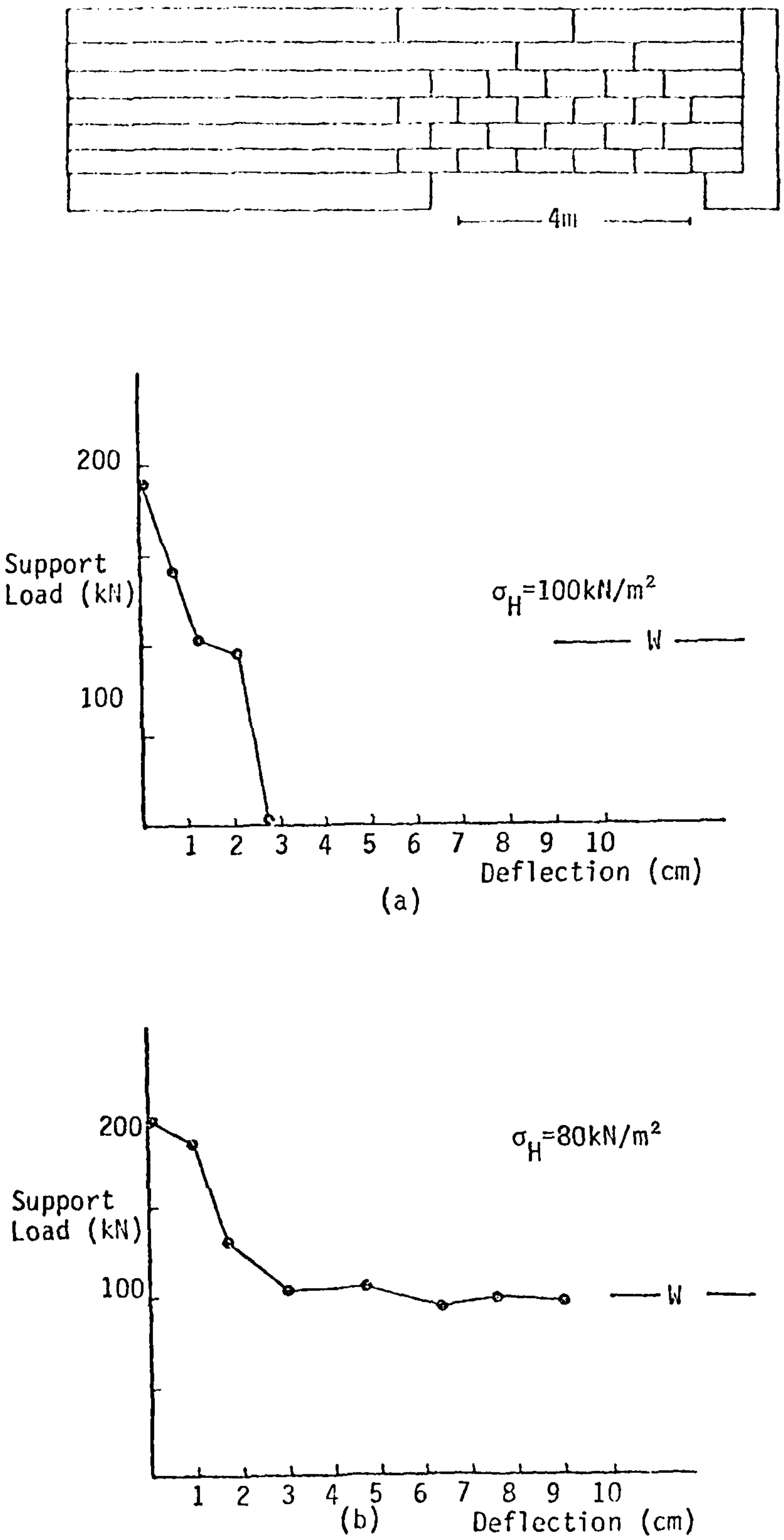
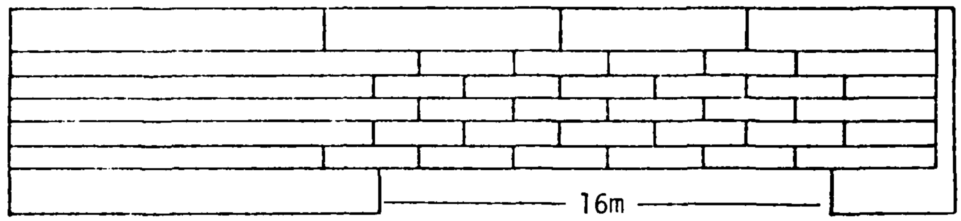



Figure 5.11 Ground Reaction Curves for 4m Wide Excavation: (a)Stabilizing Horizontal Stress; (b) Insufficient Horizontal Stabilizing Stress.

not significantly higher than the value where failure would occur if no support system was present. The end result is the same as that seen in higher stress situations presented for the six meter wide excavation. The support requirements drop to zero at a roof deflection of approximately three cm, but in the case of the four meter wide excavation there is a noticeable kink in the ground reaction curve occurring at the value of the load corresponding to the potential ultimate roof load. This probably reflects the need for finite displacement to occur before rotation of the blocks can devleop the arch necessary to stabilize the roof. The second part of the figure presents the ground reaction curve for the situation where the horizontal stress alone is insufficient to stabilize the mass. Again, the behavior of the roof indicates that the support requirements approach a constant level with increasing deflection of the roof. Note that the value of the required support resistance is again given by the potential ultimate roof load W.

The tendency for the ground reaction to indicate a constant value of the required support force was observed in the majority of the cases examined. Exceptions to this observed behavior were rare; one example will be presented shortly. The three ground reaction curves presented in Figure 5.12 are representative of a number of calculated mass responses and indicate that the rock load for which supports should be designed is represented fairly accurately by the potential ultimate roof load. Figure 5.12(a) and (b) both represent situations of insufficient horizontal stabilizing force for a



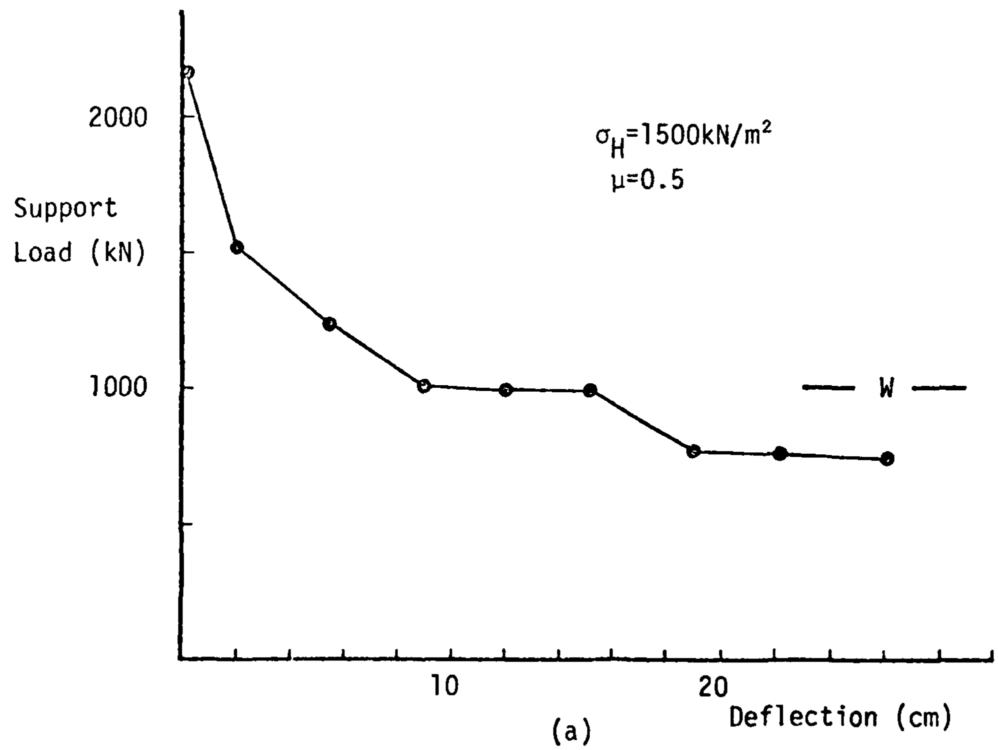
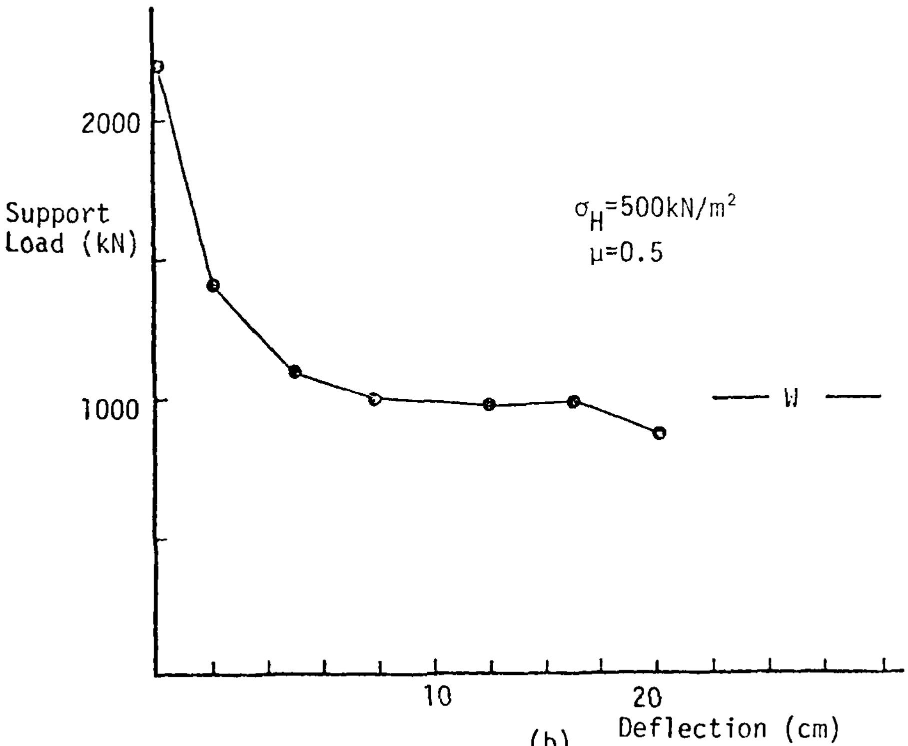
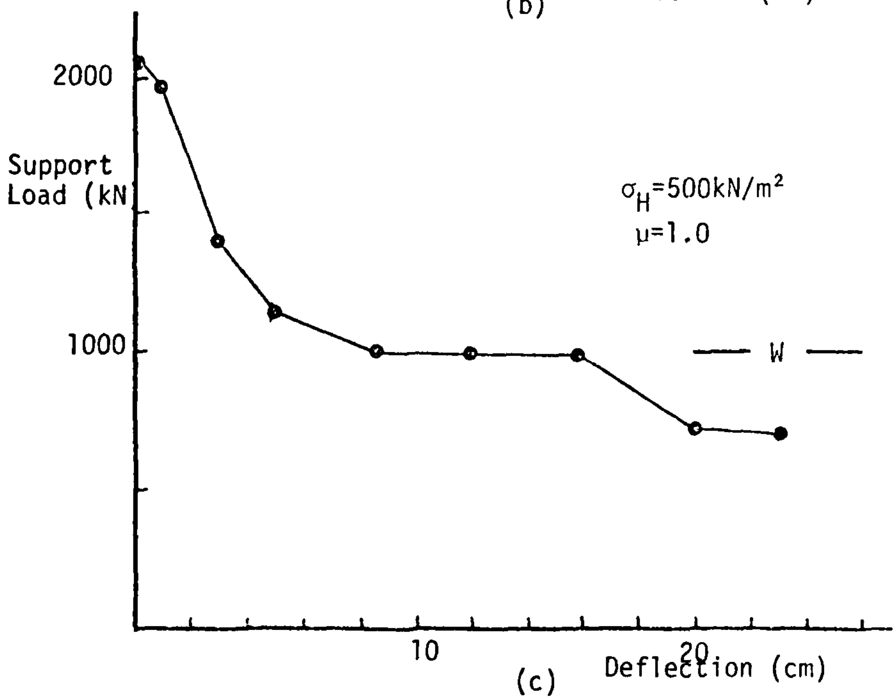




Figure 5.12 Ground Reaction Curves for a 16 meter Wide Excavation Illustrating the Consistancy of Constant Support Load with Decreasing Horizontal Stress and Friction Coefficient.




(b)




(c)

Figure 5.12 Continued.

16 meter wide excavation; part (b) however, represents a situation of much lower horizontal stress. The general shape of the ground reaction curves is, nevertheless, similar. The third ground reaction curve also represents low stress conditions but indicates the effect of increasing the friction coefficient of the joints. As can be seen, the same constant load requirement emerges. The major effect of the higher friction coefficient is to decrease the rate at which the ground reaction curve drops to the final, constant level. This is also representative of other cases observed; an increase in the friction coefficient has little effect on the ultimate support requirement.

The three curves presented in Figure 5.12 also indicate a characteristic decrease in the support load requirements with further roof deflection. This decrease in required support was observed most frequently in problems involving blocks with a low aspect ratio. This behavior typically corresponded to roof deflections of the order of 10 to 20 percent of the block thickness and is indicative of bed separation occurring as an arch develops in the second row of strata above the excavation. This behavior was not observed in situations involving higher aspect ratios, probably owing to the tendency of this type of model to fail by sliding rather than arching.

The presentation of the calculated ground reaction curves has indicated that two general behavior patterns emerged from this investigation: first, ground reaction curves for masses which would have been stable without external support reflect this

stability by indicating no required load after a small finite deflection of the roof; and second, ground reaction curves for masses which would have failed without external support indicate that the required support is a constant value, typically given by the potential ultimate roof load of the model. The first result was not unexpected; the second result, however, requires an attempted explanation.

Figure 5.13(a) illustrates a 10 meter wide excavation; the distribution of contact forces for the case of no external support is illustrated in part (b) of the figure. The contact force distribution represents clearly the situation observed for other stable excavation geometries; well developed roof and ground arches can be seen along with minimal vertical force transmittal within the zone of potential finite displacement. The contact force distributions illustrated in Figure 5.13 (c) and (d) are representative of conditions prevailing in the presence of external support. The relative roof deflections of the roof corresponding to these force distributions are indicated on the ground reaction curve for the mass in part (e) of the figure. The first force distribution indicates that the presence of the support results in an initial inhibition of the development of the roof arch and allows vertical force transmittal through the zone of potential finite displacement. Part (d) of the figure is indicative of conditions on the constant portion of the ground reaction. The roof arch is partially developed, but the presence of the support is preventing the block rotations necessary for minimizing the

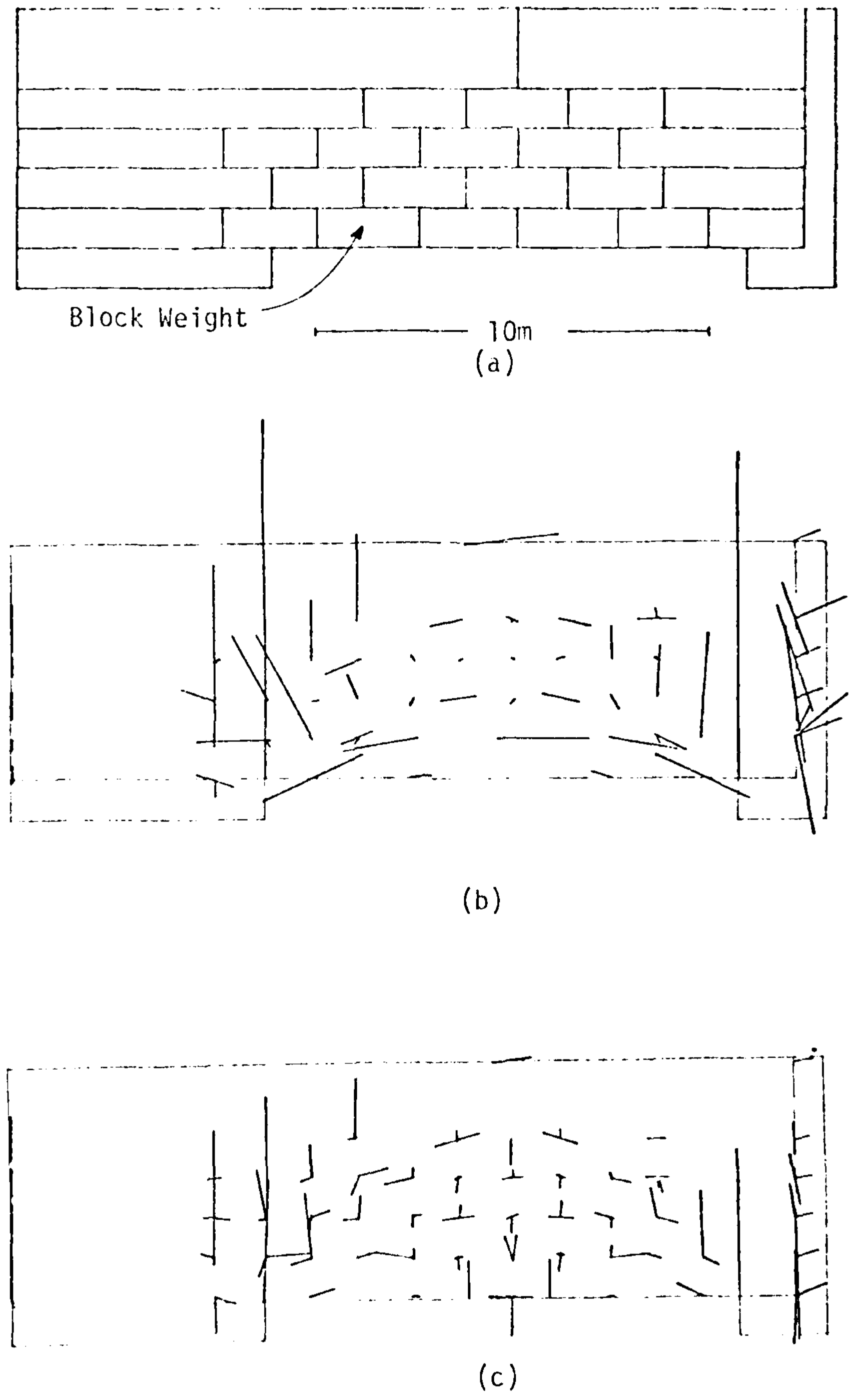
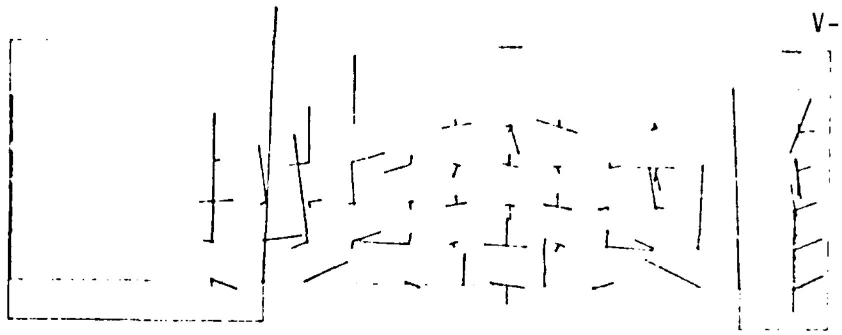
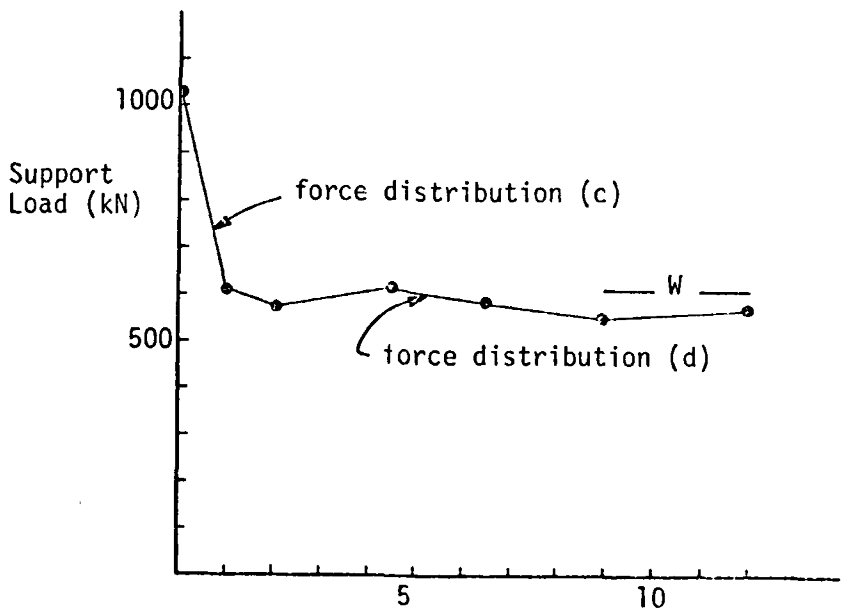



Figure 5.13 Contact Force Distributions for Indicated Model(a); (b) No External Support; (c) and (d) External Support; Relative Deformation Indicated on Ground Reaction Curve (e).



(d)




(e)

Figure 5.13 Continued.

vertical force transmittal within the zone of potential finite displacement.

At this point it is opportune to emphasize the "physical" properties governing the behavior of the joints. In the present formulation of the Distinct Element program, the joints are assumed to be smooth, planar surfaces with shear strength due only to frictional resistance. This characterization neglects two important parameters of joint behavior: cohesion and dilatancy. Cohesion along joint surfaces is significant in determining the initial strength of a joint; once failure begins, cohesion is typically lost, so it is probably realistic to characterize a failing jointed mass as cohesionless. The dilatant properties of joints are relatively well known, at least qualitatively. The main effect of the dilatant behavior of joints is a volume increase with shear movement resulting in an increased normal stress on the joint and thus, an increased resistance to shear. In order to arrive at the ground reaction curves presented in this section the behavior of the joints was thus highly idealized. It is therefore unrealistic to expect that the ground reaction curves presented are characteristic of the behavior of all jointed masses.

As a final example of a ground reaction curve for an excavation in a jointed rock mass, a situation is presented where the typical, constant ultimate load requirement was not observed. The case under consideration, a 24 meter wide excavation where the jointing defines blocks having an aspect ratio of 0.1, is illustrated in Figure 5.14. The ground reaction curve, also

illustrated in the figure, is seen to possess characteristics markedly different from those typically observed. The most significant of these are the lower rate of decrease of the curve, an upswing of the curve with increasing roof defleciton, and values of the support requirements significantly in excess of the potential ultimate roof load. As an aid to understanding this departure from the typical behavior, it is instructive to examine the geometry of the deformed state of the rock mass as indicated in parts (b) and (c) of the figure. As can be seen, the maximum deflection of the roof is not occurring at the support point as was the case in the other geometries examined. Additionally the horizontal force is causing the relatively slender lower strata to buckle. The result of this action is that the lower row of blocks is actually "prying" the support block away form the strata and thus acting to increase the load on the support.

This example points out several shortcomings of this analysis which should be enumerated. First, it indicates the inadequacy of modeling the support system as a single point since multiple "blocking points" could have prevented the off center maximum deflections and possibly could have resulted in a different response. The other major shortcoming of this analysis is the infinite strength of the blocks. In a real situation the behavior indicated in the figure would probably result in fracture of the blocks long before the situation indicated in part (c) of the figure could have developed.

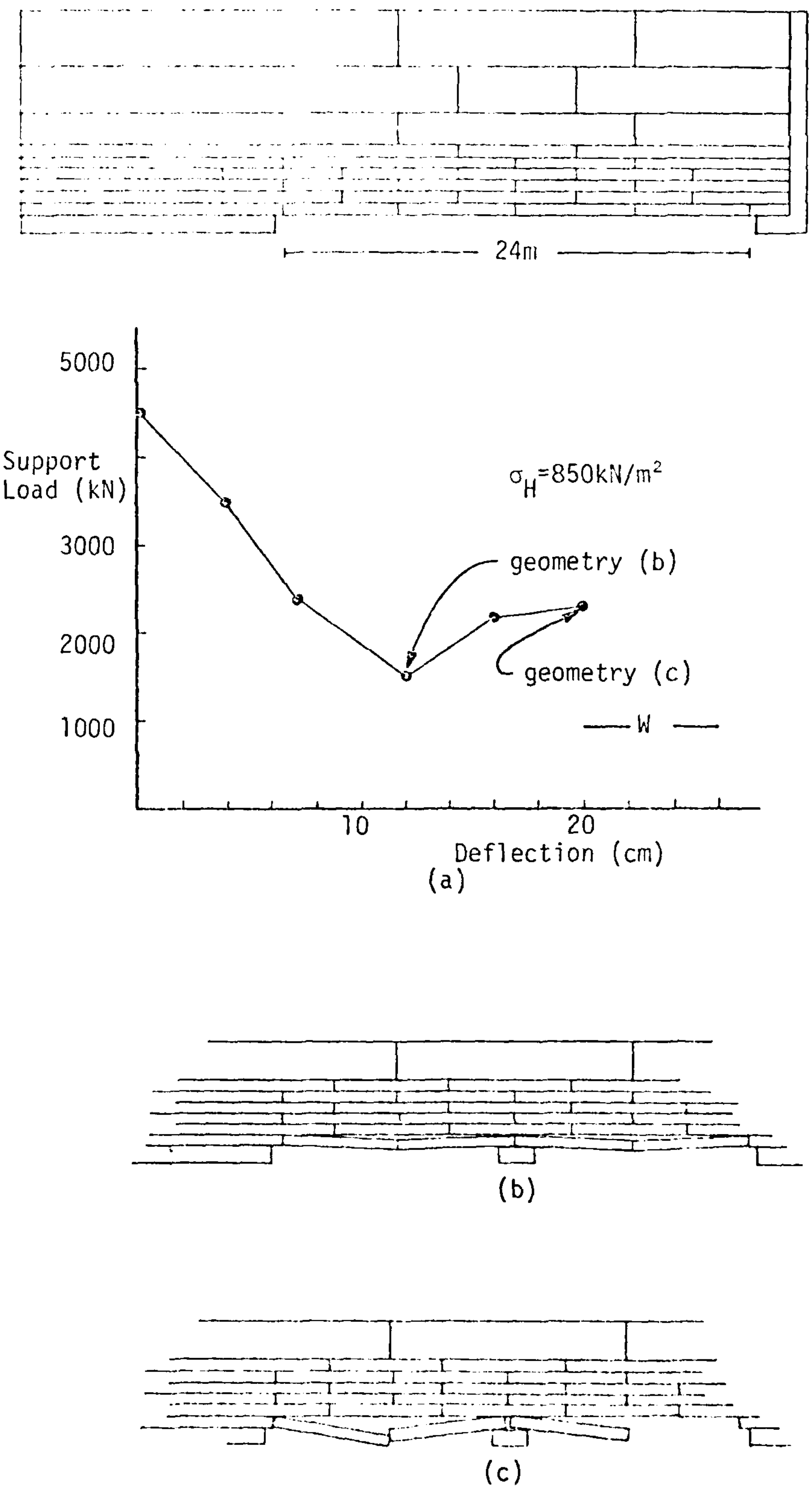



Figure 5.14 Ground Reaction Curve and Displaced Geometries for 24 meter Wide Excavation.

The modeling of jointed excavation roofs presented in this section lead to the conclusion that the ultimate load to be resisted by the support system could be predicted, in the majority of cases, by the potential ultimate roof load described in Chapter 5.2.3. The ultimate loads predicted by the ground reaction curves are summarized in Figure 5.15. Neglecting data from analyses similar to that just described, a relationship between the ultimate support load and the span of the excavation can be seen. This relationship was found to be a function of the aspect ratio of the blocks, but relatively insensitive to the friction coefficient of the joints. The relationship between the support load required and span is given approximately by:

$$L = n \; B^2 \qquad 5.14$$

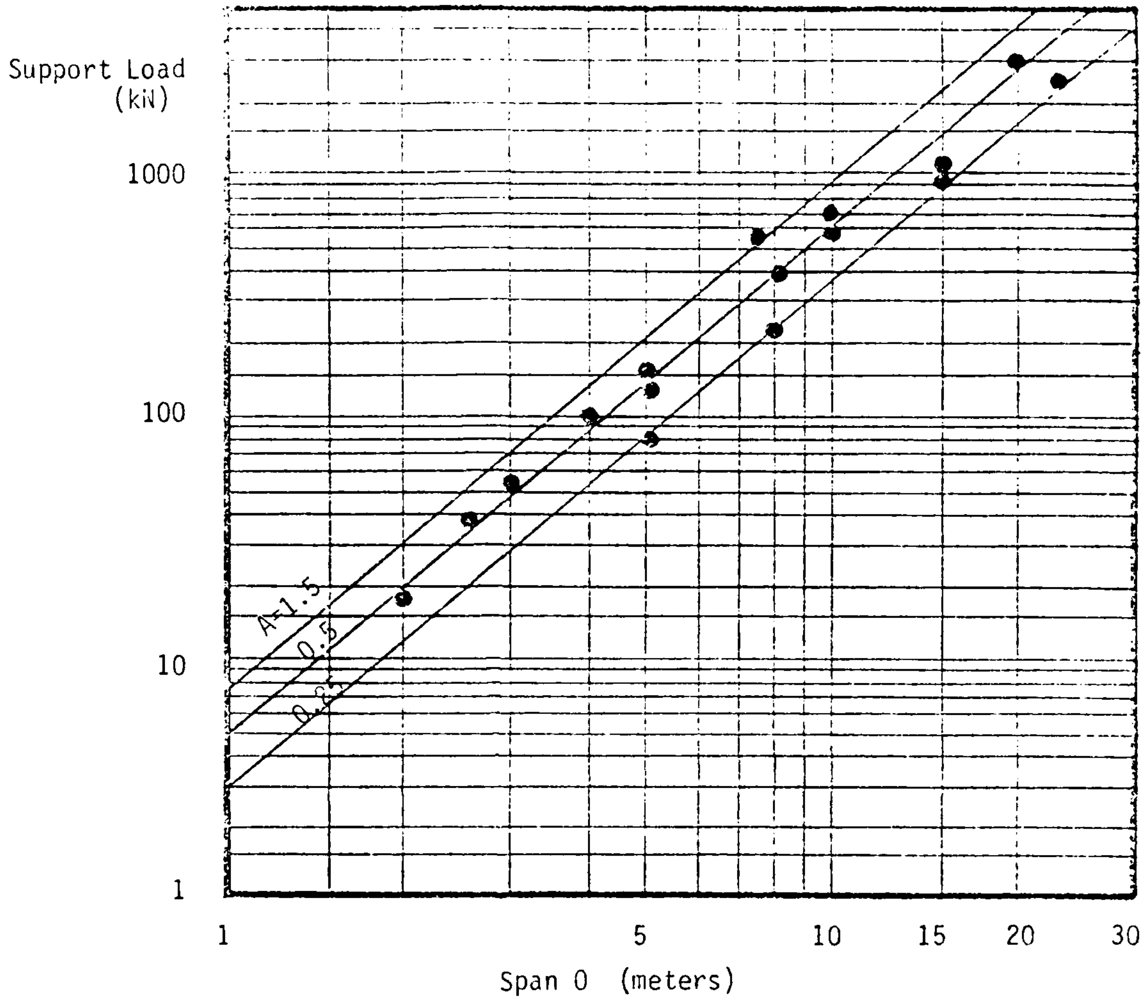
where

$n = 2 + 5A$, and

$A$ is the block aspect ratio.

### 5.4.2 The use of the Distinct Element method in the design of support systems for excavations in jointed masses

The ground reaction curves presented in the preceeding section indicated that in response to the idealized assumptions of joint behavior utilized in the analyses, the support force required for stability was seen typically to be a function of the geometric properties of the excavation. In particular, the ultimate resisting force was found to have been given approximately by the potential ultimate roof load, which could be calculated with the aid of

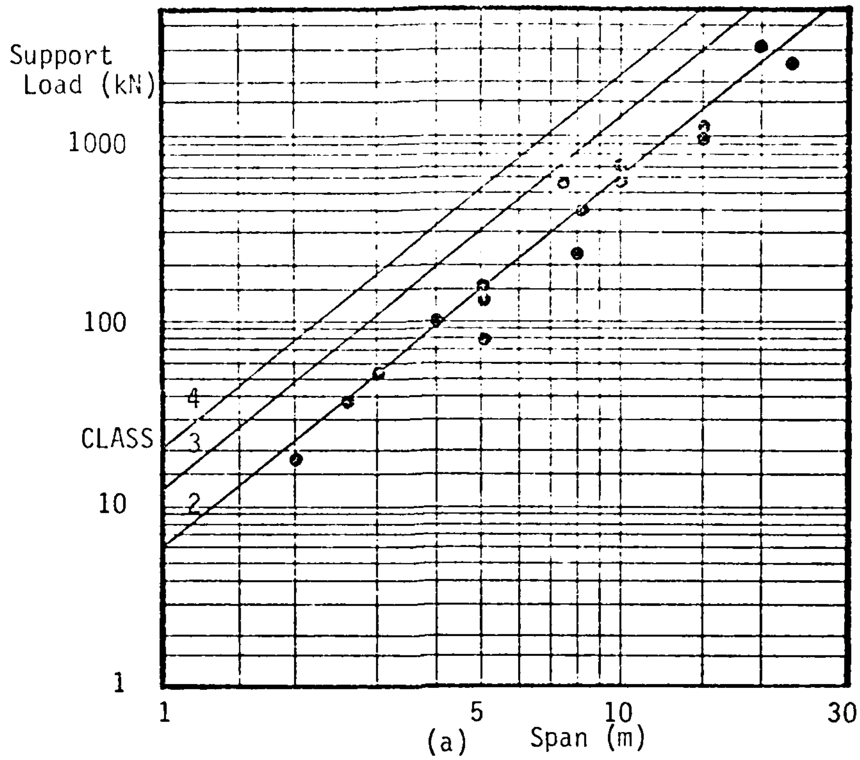



Note: A is the aspect ratio defined by the jointing.

Figure 5.15 Summary of ultimate loads on support system for cases where the mass did not stabilize independently of the support system.

Figure 5.4 or approximated by equation 5.17 in terms of the span and the aspect ratio of the blocks. In this section is presented a comparison of these results and the observed load-span relationship with several of the empirical schemes to see if a correlation exists. To ensure that the discussion doesn't stray too far from reality, actual design data from several underground excavations is also included.

The primary purpose of this investigation was to see if the Distinct Element calculated response of an excavation in jointed rock, taking account of mass/support interaction, could be correlated to "dead weight" load schemes such as that proposed by Terzaghi. Several comparisons of this type are presented in Figure 5.16. Parts (a) and (b) of the figure present the total load to be resisted as a function of span as estimated by the methods of Terzaghi and Stini. The Terzaghi load classes two, three and four are included on the graph and it can be seen that classes two (hard, stratified) and three (massive, moderately jointed) bracket the data nicely. It should be noted that the models examined could be included in class four (blocky and seamy) and as such, would indicate that Terzaghi's method is non-conservative. Similarly, the Stini estimates for classes two, three and four have been plotted in part (b) of the figure and compared to the Distinct Element responses. Examination of the comparison presented in the figure indicates good agreement with the Stini classes two (nearly stable) and three (lightly broken) for spans greater than about eight meters in width, but the agreement becomes



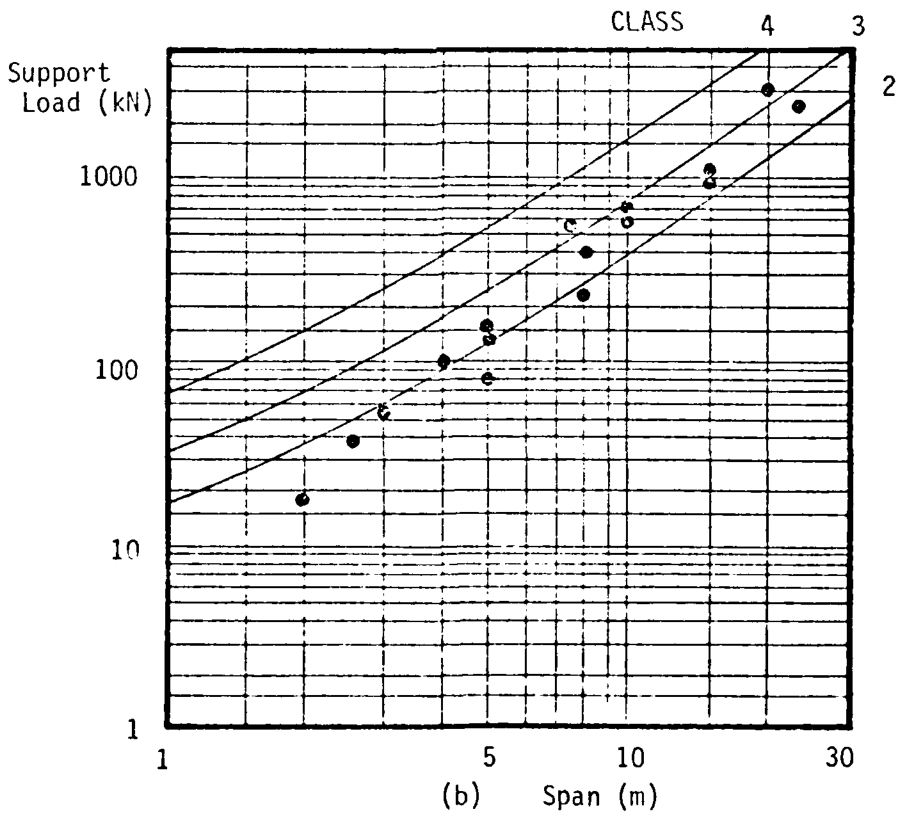
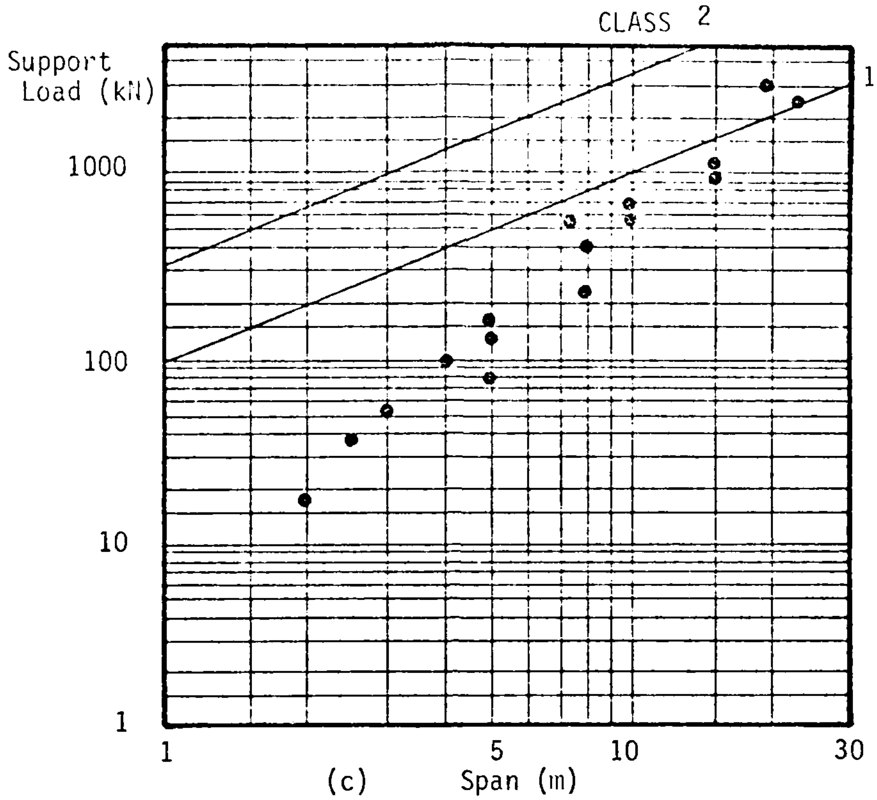
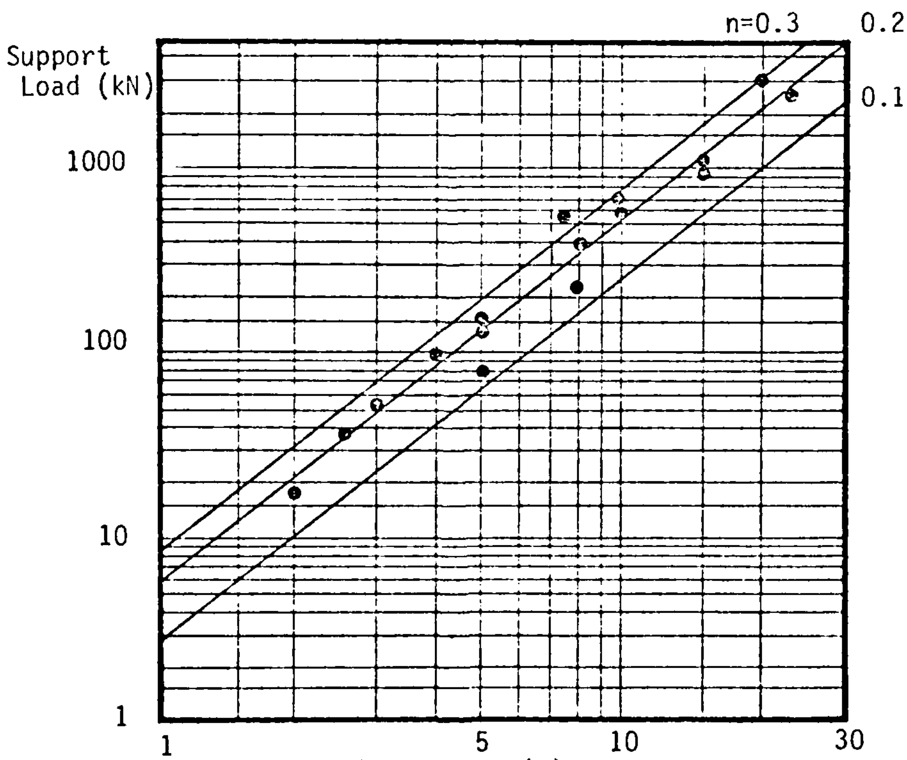




Figure 5.16 Comparison of Distinct Element calculated required support load with: (a) Terzaghi estimates, (b) Stini estimates.




(c)




(d)

Figure 5.16 continued, (c) Bierbaumer estimates, (d) Cording estimates.

less good with decreasing span.

The constant pressure theory of Bierbaumer is compared to the data in part (c) of the figure. There is a semblance of agreement for spans in the 25 to 30 meter range; extrapolation of the trends of the data, however, indicates that this agreement is probably coincidental (two non-parallel lines must intersect somewhere). It is unlikely that Bierbaumer had access to data from excavations of this width; for spans in the two to five meter range, there is no correlation between Bierbaumer's method of predicting the load and that calculated by the Distinct Element method.

The final comparison presented in Figure 5.16 utilizes the load estimation scheme described by Cording et al. (1971). This scheme will be described in some detail presently but for now it is sufficient to note that the parameter n is based upon actual design data. The fit of the curves to the Distinct Element data is quite good.

This comparison would certainly be more meaningful if the actual design data for excavations in which the support system had failed were available. The next best information is design data for excavations that did not fail; this is what is available and it will be used in further comparison. A significant number of actual support pressure designs were summarized by Cording et al. (1971); this data is presented graphically in Figure 5.17(a). Cording et al. attempted to correlate RQD to support pressure by means of what they termed the Terzaghi Design Envelope (Figure 5.17(b). This

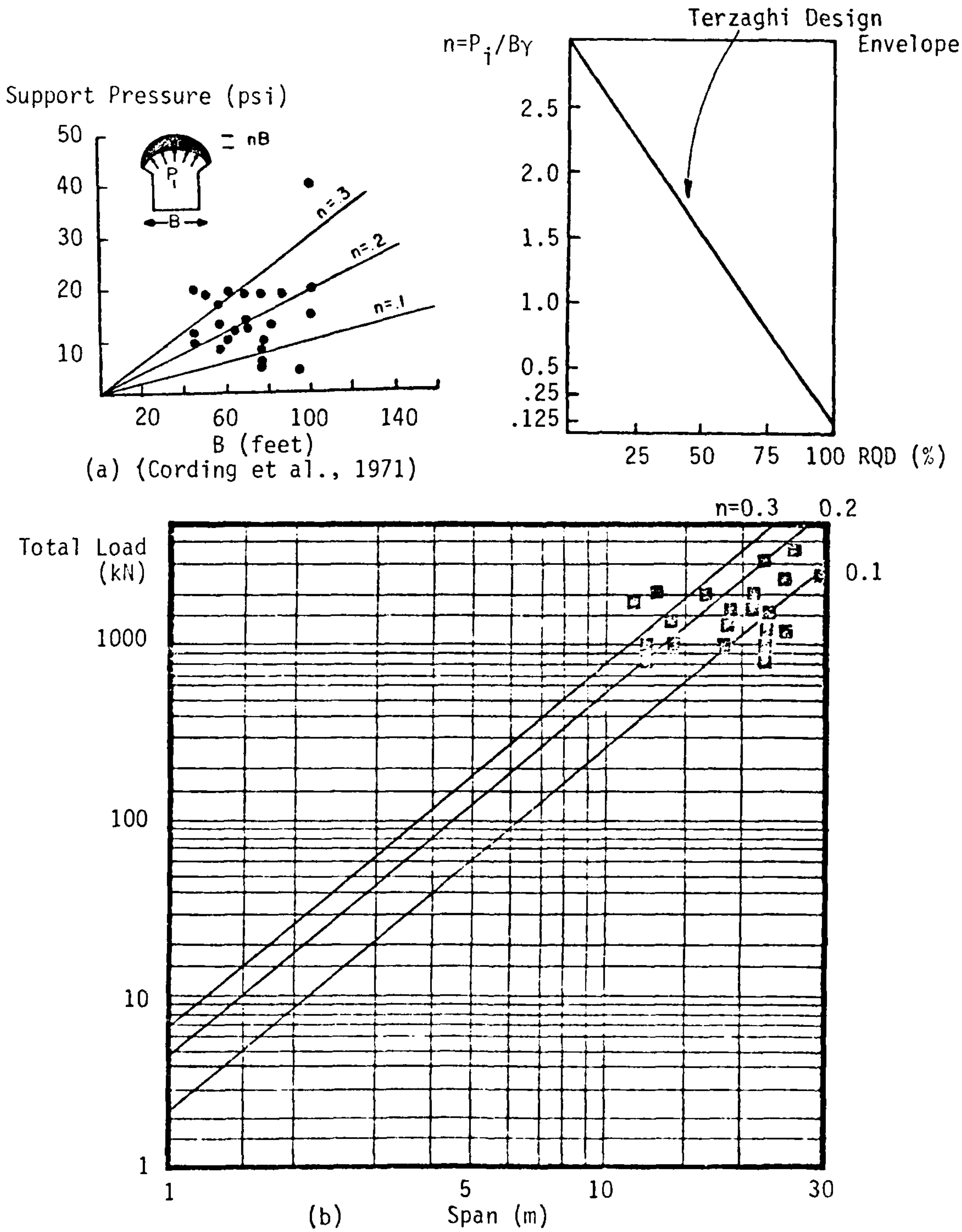
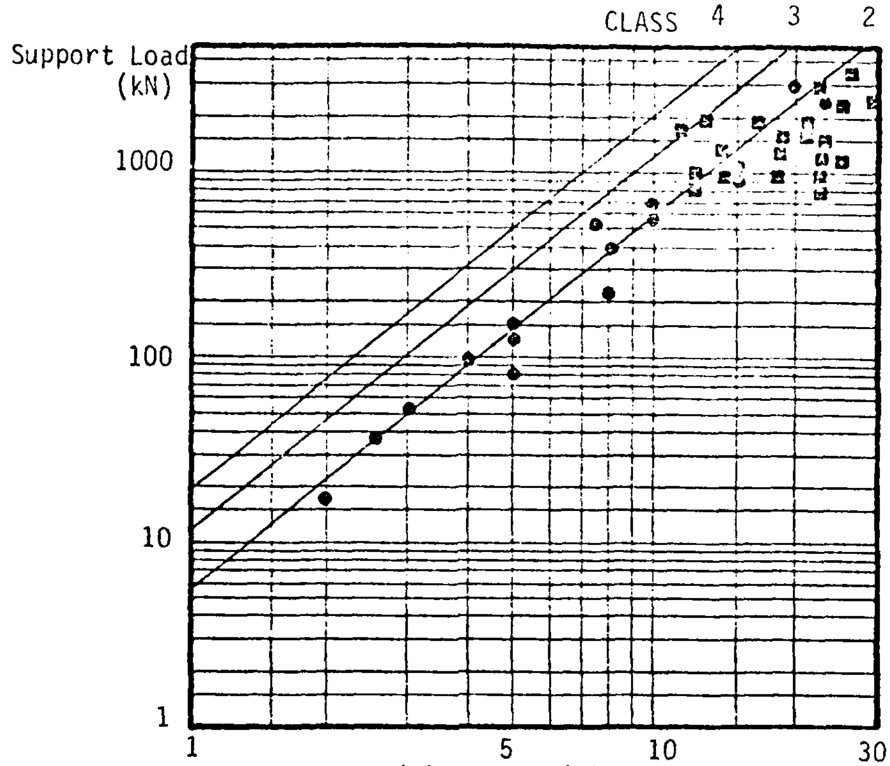


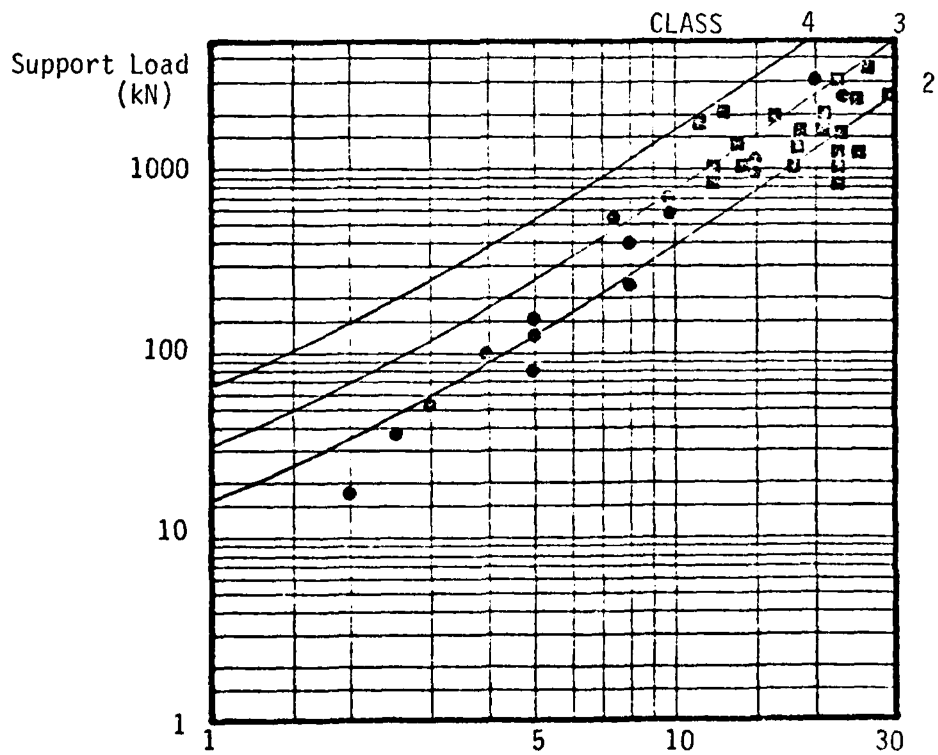

Figure 5.17 (a) Summary of support pressure design data used for cavern excavations, (b) logarithmic representation of total load.

data has been replotted in part (c) of the figure to reflect total loads rather than pressures. This classification scheme, then is essentially similar to Terzaghi's but predicts a smaller total load or pressure when the value of RQD is very high. It must be emphasized that the data represents design pressures for excavations that are stable. Invariably, the data then represents an incorporated factor of safety or an overdesign. Additionally, most of the caverns have arched crowns; in general higher support pressures would be required for excavations having flatter roofs. It can be seen, therefore, that the comparison of this design data and the required loads calculated by the Distinct Element program is not strictly valid. It is not suggested that the amount of over design and the required pressure increase in the case of the flat roof cancel each other, but that the combined result gives a valid basis for comparison.

Four of the graphs presented in Figure 5.18 are identical to those presented in Figure 5.16 except that the design data summarized by Cording et al. has been incorporated on each of the plots. Most of the comments presented earlier are still valid, but additional comment is required in several instances. The conservative nature of the Terzaghi rock load estimates is more apparent when the data of Cording et al. is added to the plot. Stini's estimates of the rock load still fit the data quite well for spans greater than 10 meters; unfortunately data for the narrower spans was not available. The rock loads predicted by

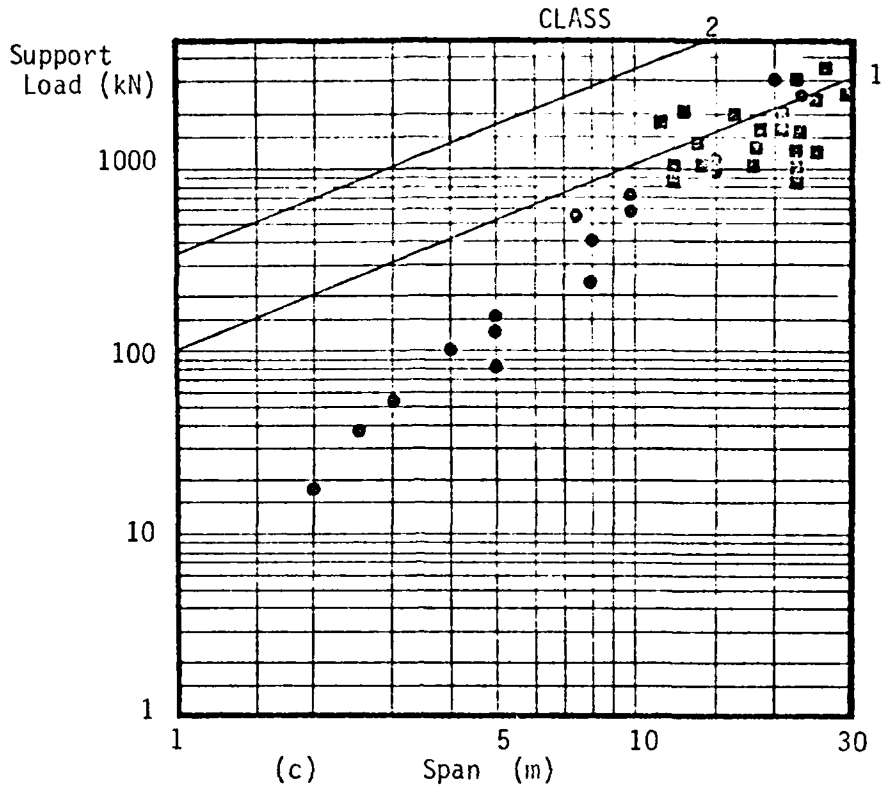



(a) Span (m)




(b) Span (m)

Figure 5.18 Summary of support loads as calculated by the Distinct Element method and reported in the literature Comparisons to metoods of: (a) Terzaghi;(b)Stini;



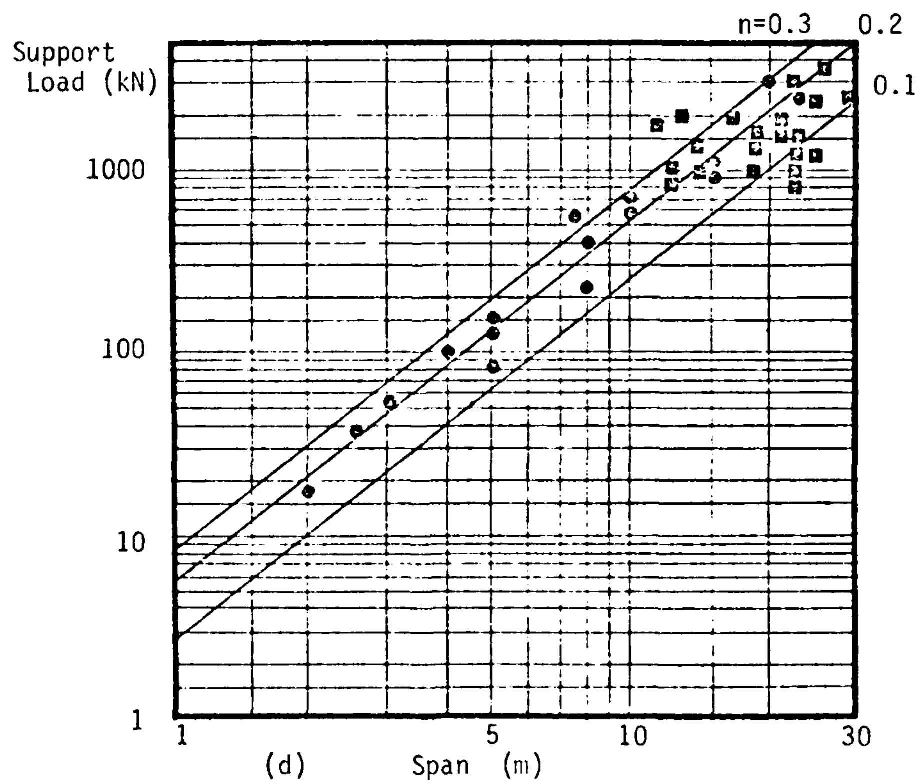




Figure 5.18 (continued) Methods of: Bierbaumer (c); Cording, et al. (d);

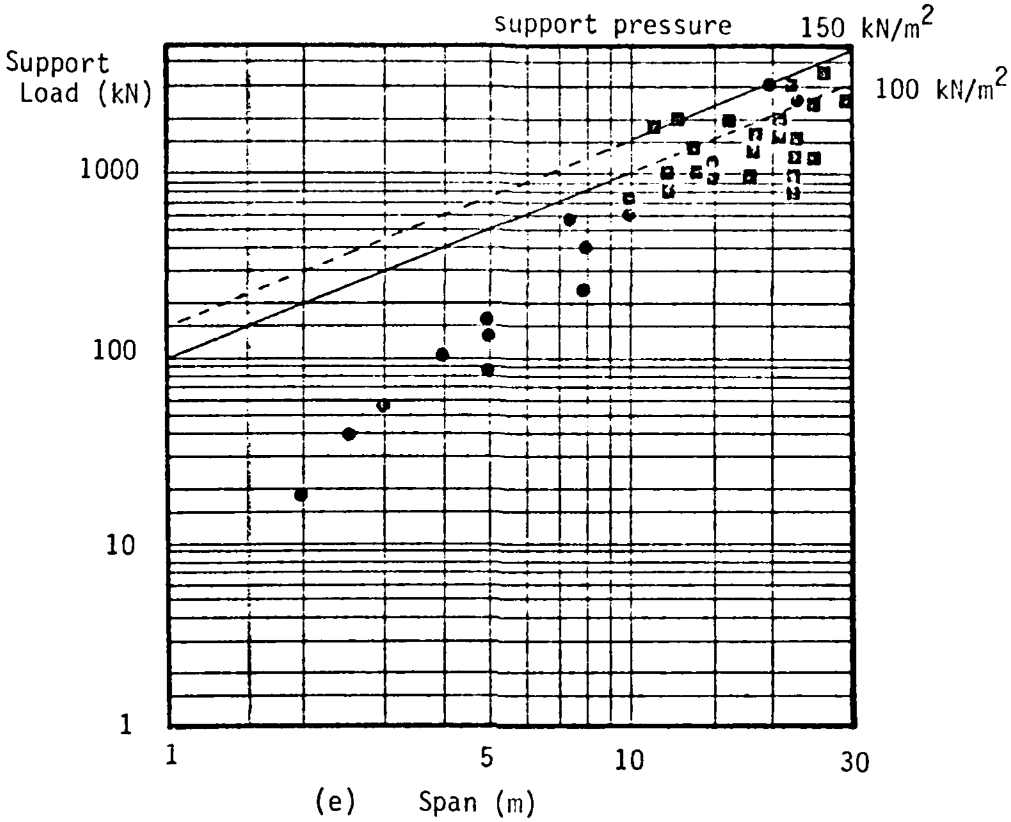



Figure 5.18 ( continued ) Method of Barton,et al.

Bierbaumer's method are still quite nonconservative in light of the actual support pressures. The estimates of the rock load as calculated by the method of Cording et al. are seen to fit the data quite well, and seems to indicate that an RQD based modification of the Terzaghi rock load estimates is a valid tool for the estimation of expected support loads in an excavation.

It is beyond the scope of this investigation to present detailed summaries of the newer classification schemes presented by Wickham et al., Bieniawski, and Barton et al. but it is relevant to include at least one of the schemes in the comparisons presented herein. Of the three methods, Barton, Lien and Lunde's was chosen for inclusion for no reason other than that the results are expressed as support pressures. Some familiarity with the method on the part of the reader is assumed.

Barton, Lien and Lunde's classification scheme requires the specification of six input quantities; the values of those quantities thought to represent the Distinct Element modeled geometries are presented in Table 5.5.

Table 5.5 Parameter Values for Rock Mass Quality Q

| | | |
|---|---|---|
| A) | RQD (Good to excellent) | 75-100% |
| B) | Joint Set Number (two joint sets) | 4.0 |
| C) | Joint Roughness Number (smooth, planar) | 1.0 |
| D) | Joint Alteration Number (unaltered) | 1.0 |
| E) | Joint Water Reduction Factor (dry) | 1.0 |
| F) | Stress Reduction Factor (low stress) | 2.5 |

The resulting Q value is found to range from seven to ten; the rock masses modeled by the Distinct Element method all fall in the "fair" category and a need for support is indicated. The indicated support pressures are 100 $KN/M^2$ for those spans less than ten meters in width and 150 $KN/M^2$ for those spans greater than ten meters in width. In these calculations an excavation support ratio (ESR) of 1.0 was assumed.

The support pressures calculated were compared to the Distinct Element calculated data and the data presented by Cording et al. The results of this comparison are presented in Figure 5.18(e). It is readily apparent that the constant support pressures suggested by Barton, Lien and Lunde's method do not adequately describe the trends of the data calculated by the Distinct Element method. Furthermore, the support pressures result in total loads that are significantly higher than the data of Cording et al. indicate would be experienced in practice.

The data calculated by the Distinct Element method during this investigation raises one serious objection to the use of the design equation presented by Cording et al. Without exception, all of the geometries modeled using the Distinct Element program had an RQD value of 100 percent. The use of the design equation postulated by Cording et al. would, in this instance, result in a significant underestimate of the amount of required support force. The value of "n" corresponding to an RQD value of 100 percent is 0.1; the majority of the plotted data, both that calculated by the Distinct Element method and that reported by Cording et al. can be seen to

lie above the curve corresponding to an n value of 0.1. Perhaps an equivalent RQD based upon seismic velocities could be calculated for the Distinct Element geometries, but it is really outside the scope of this investigation to attempt a correlation of this type.

Figure 5.19 presents a summary of the required support force as a function of span for those masses investigated by the Distinct Element method; also included in the figure is the actual design data summarized by Cording et al. The curves indicating the trend of the data have, in this instance, been calculated using equation 5.14. The presented curves fit the data as well as those suggested by Cording et al.; however, in this case the curves are a function of the aspect ratio of the blocks formed by the jointing. It is not immediately clear that there should be a correlation between RQD and aspect ratio of the blocks. It certainly would be feasible to estimate the block aspect ratio if directionally biased RQD data were available, but RQD data is not typically recorded in this manner.

It was not the intent of this section to deduce a relationship between RQD and the aspect ratio of the jointing; what was desired was computationally based verification of empirical rock load estimation schemes. The properties of the basic model chosen for investigation indicated that a reasonable estimate of the upper limit to the amount of load to be resisted by the support system could be calculated in terms of the geometric parameters of the rock mass and excavation. The eventual results indicated that this upper limit, the potential ultimate roof load, was actually the

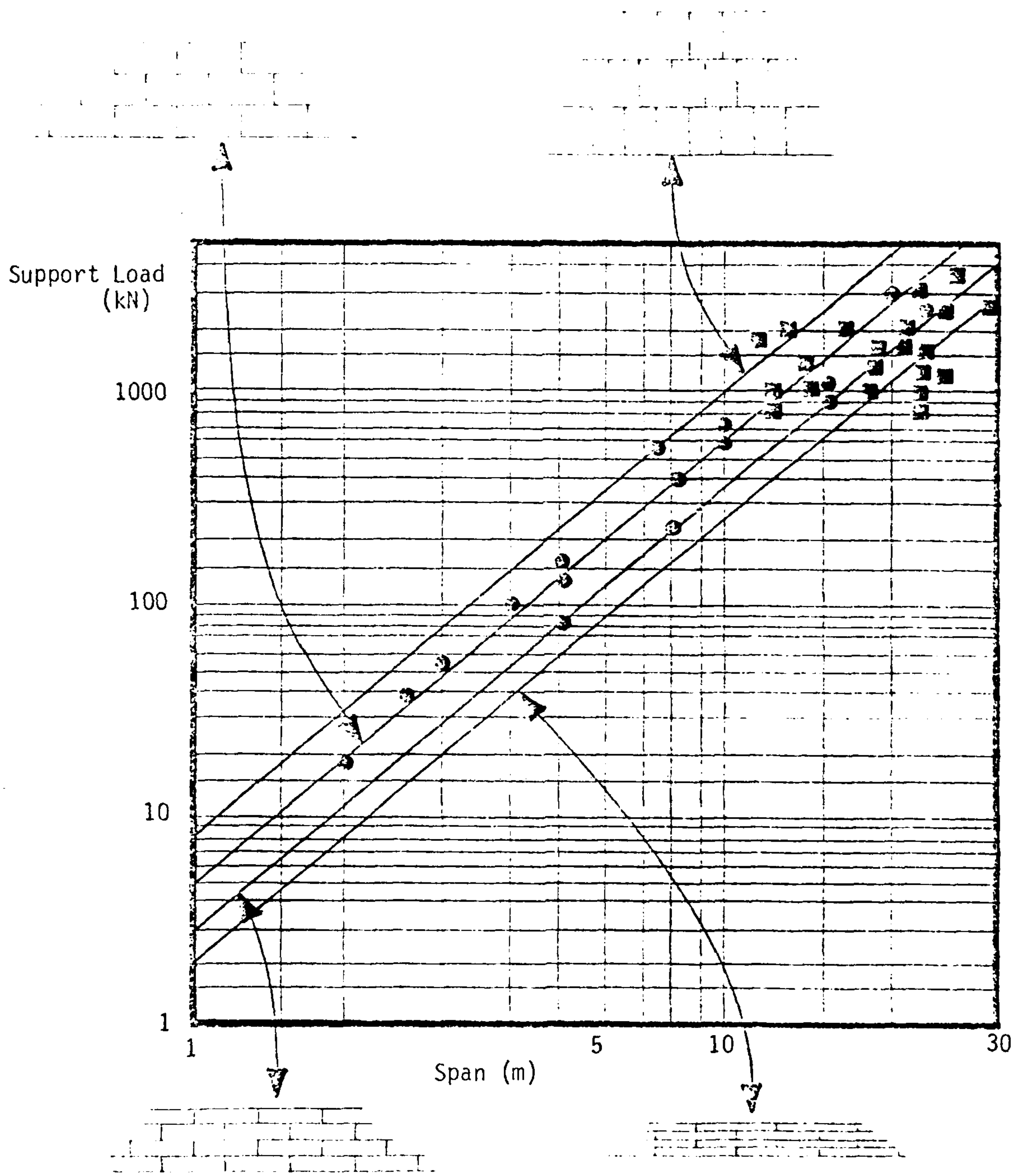



Figure 5.19 Summary of Distinct Element calculated required support loads and design data presented by Cording et al., also illustrated are the various aspect ratios.

value for which the supports should be designed. This value could be calculated by equation 5.8 or estimated in terms of the aspect ratio of the blocks. Comparison of the results to actual design data indicated a high degree of correlation.

## 5.5 The Effect of Joint Interlocking on the Ground Reaction Curve

The rock mass models that have been presented previously possessed the characteristics of the basic model described in Chapter 4.3. The basic response characteristic of this model is that a triangular wedge of material separates from the rock mass as failure occurs. Before the basic model for study was selected the behavior of a number of varied joint geometries was investigated. One of the most striking factors to emerge from those analyses was the sensitivity of the rock mass behavior to joint orientation. Of particular interest was the observation that geometries initially observed to be unstable, often stabilize after a finite displacement. This sensitivity of rock mass behavior to joint orientation can be illustrated for a particular mass configuration by varying the joint orientation without changing any of the other parameters. The ground reaction curve provides the means for quantifying the observed differences in roof behavior.

The basic rock mass geometry to be investigated is illustrated in Figure 5.20(a). The model represents an excavation in a medium with two well defined joint sets. The major set dips gently and is continuous; the minor set is somewhat variable in orientation, crosses the major set approximately at right angles on the average and is discontinuous. Exposed in the upper right hand side of the excavation is an almost triangular wedge of material bounded by joints with a friction angle of $5^{\circ}$; all other joints have a friction angle of $26.5^{\circ}$. The triangular wedge represents a shear zone and its presence can be expected to govern, or at least severely

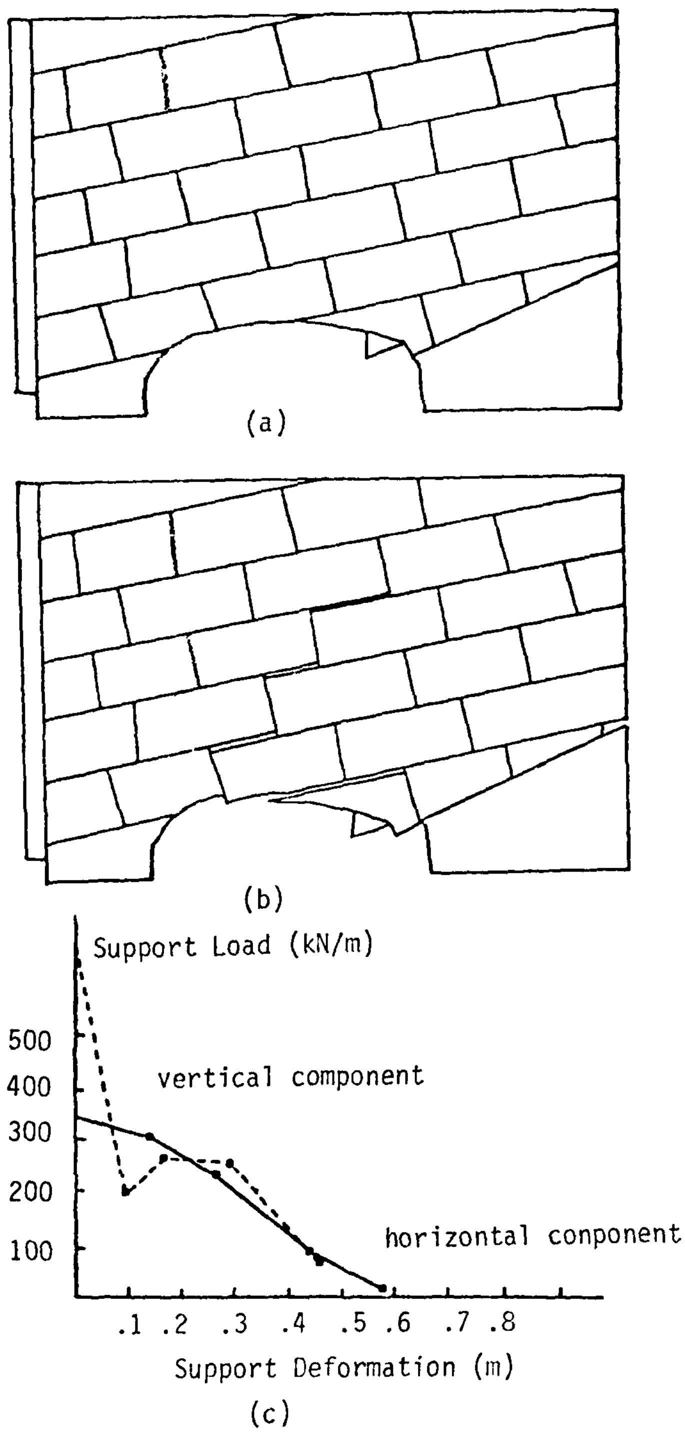


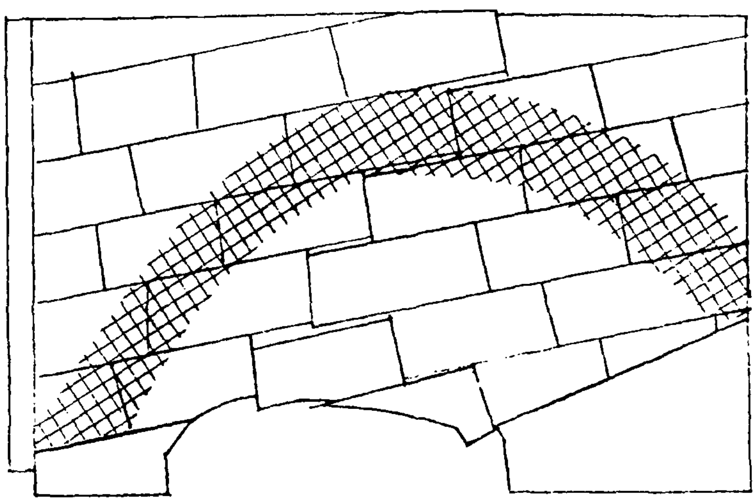

Figure 5.20 Ground reaction curve for a model where arching acts to stabilize the mass.

influence, the behavior of the rock mass.

The eventual deformed state of the rock mass is illustrated in Figure 5.20(b). Immediately obvious upon inspection of the figure is the fact that the roof has stabilized as evidenced by the lack of contact between the roof and the leftmost portion of the shear zone. This stabilization is the result of joint interlocking leading to the formation of the roof arch which acts to transfer the loading forces to the abutments. The roof and ground arch can be seen in a plot of contact vectors but tend to be observed by the plotted joints. In order that the arches could be seen, the regions corresponding to the high contact forces have been outlined and shaded; the ground and roof arches corresponding to the rock mass of Figure 5.20 are illustrated in Figure 5.21(a).

A quantitative expression of this arching behavior is indicated by the ground reaction curve which has been separated into its vertical and horizontal components, presented in Figure 5.20(c). The vertical component curve demonstrates a general decrease, with displacement, in the amount of load to be resisted by the supports. In fact, at a deformation of 0.5m the only vertical load on the support is the weight of the leftmost triangular portion of the shear zone. This decrease in load corresponds to the development of the roof arch with vertical displacement and the subsequent transfer of vertical force to the sides of the excavation. The horizontal component indicates that at a deformation of 0.5m the force is practically zero. The reason for this can be seen by reference to the diagram showing the ground and roof arches, Figure 5.21. The

(a)



(b)

Figure 5.21 Pressure distributions in: (a) a stabilized roof, (b) a failing roof.

roof arch transfers load onto jointed blocks relatively near the excavation. The resultant of this abutment force tends to push the blocks back into the rock mass and thus acts to reduce the horizontal load on the supports. Note that if the amount of deformation could be tolerated, this roof would stand unsupported.

The measurement of joint orientations in the field is always subject to a high degree of subjectivity; since the joints can only be observed at outcrops, local undulations can introduce a degree of uncertainty in the measurement of the true attitude of the discontinuities. The significance of accurately determining the joint orientations is dramatically illustrated in the second part of the example.

Figure 5.22(a) illustrates a rock mass geometry that at first glance appears identical to that presented in Figure 5.20(a). Closer examination of the figure indicates that although the major joint sets have identical attitudes in both figures, there are minor variations in the orientation of the discontinuous cross jointing. In particular, note the small cross joint exposed on the left hand side of the excavation which has been emphasized in both figures by indicating its loaction by an arrow. It was noted that on the average the cross jointing was approximately perpendicular to the main joint set. An uncertainty of five degrees in the measured orientation of a joint is not a large number, nor are variations in true joint inclination of from five to ten degrees uncommon. Whether the variation between the models arises from errors in measurement or true deviations in joint

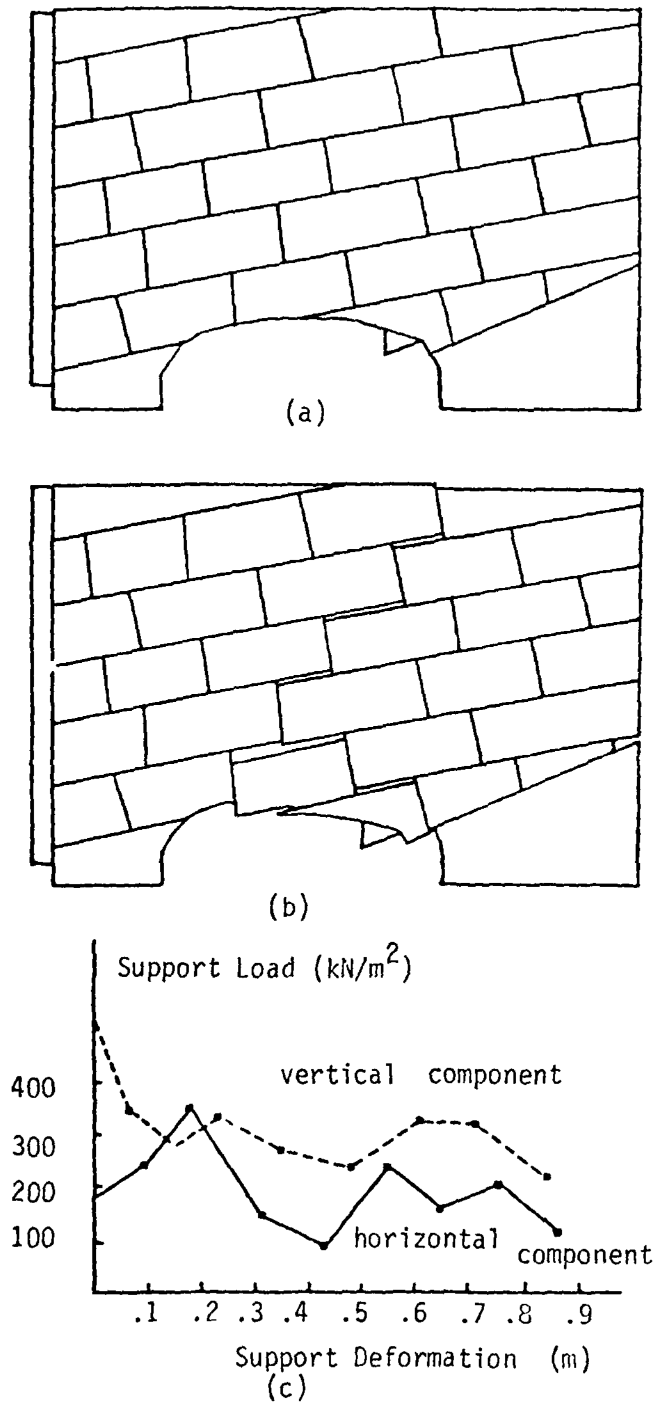



Figure 5.22 Ground reaction curve for a model where arching does not act to stabilize the mass.

attitudes is not significant. What is important is the fact that the behavior of the two models changes markedly in response to relatively minor changes in joint orientation.

One stage of the deformation of the model is illustrated in Figure 5.22(b). Examination of this figure indicates a more widespread disruption of the roof than in the previous model but even more importantly, there is continuous contact through the roof down to the support.

Once again the ground reaction curve illustrated in Figure 5.22(c) and separated into its vertical and horizontal components provides the means to quantitatively describe these observations. The most striking dissimilarity in the ground reaction curves is that the second model is characterized by required support loads that do not diminish with increasing displacement. This roof is completely unstable and requires an external support system. The required support is relatively constant with deformation up to a displacement of almost one meter.

The instability of the roof is indicative of the lack of formation of the roof arch. This is indeed the case as can be seen by reference to Figure 5.21(b). The magnitude of the force to be resisted by the supports is limited by the full development of the ground arch. The lack of development of the roof arch prevents the mass from stabilizing and necessitates the emplacement of an external support system.

It is of interest to compare the actual support loads determined from the preceeding analyses to the theoretical values as

predicted by Terzaghi's method. The characteristics of the models indicated that the proper classification for these masses was the hard stratified rock category. This category is typified by little resistance against separation along strata boundaries and the weakening of the strata by transverse joints. The moderately jointed rock category requires intimate block interlocking or healed fracture whereas the blocky and seamy category requires blocks which are separated along joints and imperfectly interlocked. The last two categories are actually the limiting cases for the hard stratified rock category.

The sum of the horizontal and vertical components of the ground reaction curves for the two previous examples are plotted in Figure 5.23. Also plotted in the figure are the values of the support load as predicted by Terzaghi's theory.

The constant value of the total support load as calculated for hard stratified rock by Terzaghi's theory is 700 kN/m of tunnel length; compared to the ground reaction curves in Figure 5.23 an over-design is indicated. For displacements less than about 0.25m the relative differences are 25 percent and 30 percent for the failing roof and the stabilizing roof respectively. For displacements greater than 0.25m the relative difference is approximately 50 percent for the failing roof and increases with displacement for the stabilizing roof. The relative difference between observed load and predicted load is seen to be significantly greater for the two support load values calculated by the equations for blocky and massive rock masses, which are 800 kN/m and 350 kN/m of tunnel

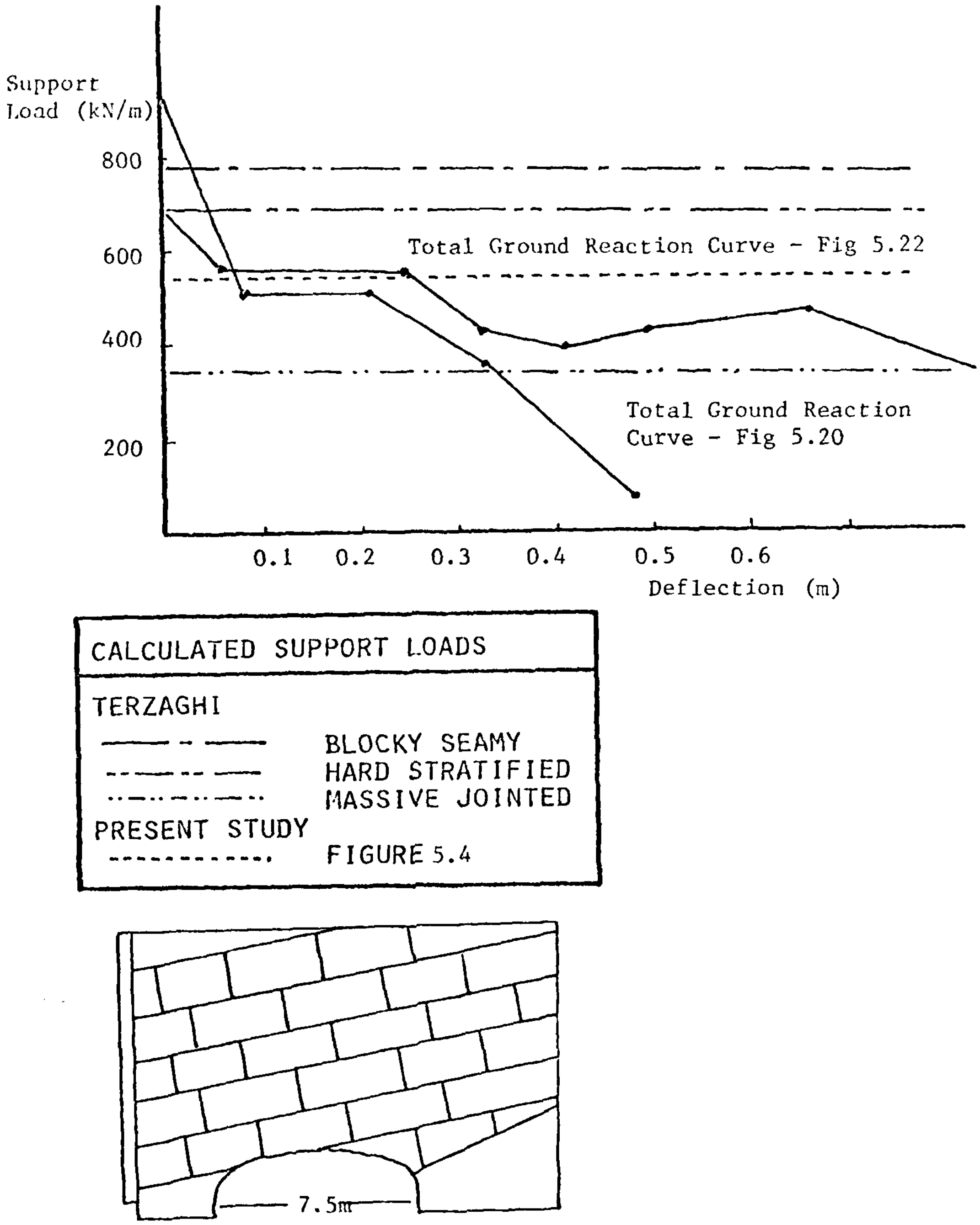



Figure 5.23 Comparison of ground reaction curves for a r f that stabilizes after deformation and a roof that fails completely with Terzaghi support loads.

length respectively.

The support load as predicted by the method developed in this chapter is also indicated in Figure 5.23. Although the model upon which the method is based involves only horizontal and vertical jointing, examination of Figure 5.21 indicates that the mechanism of load transfer in these two examples is similar to that observed in the basic model. The parameters needed to use the design chart presented in Figure 5.4 are illustrated in Figure 5.23; the span is 7.5m, the block width is 3m, the block thickness is 1.6m and the weight density of the material is 26 $kN/m^3$. The potential ultimate load to be resisted by the supports is found to be 545 kN/m. This value is plotted with the ground reaction curves in Figure 5.23 and is seen to agree quite well with the required support loads indicated by the ground reaction curves. For displacements less than about 0.25m the relative differences are approximately 5% and 10% for the failing roof and the stabilizing roof, respectively. For displacements greater than about 0.25m the relative difference is about 15% for the failing roof and increases with displacement for the stabilizing roof.

## 5.6 Summary

The design of underground excavations, particularly the design of the support system is largely based upon precedent. The summary of methods commonly used to predict support load pressures indicated that the earlier methods categorized support requirements by subjective, qualitative descriptions of the rock mass. The more recent methods have introduced some measure of objectivity into the classifications, and strengthened the data bases underlying the schemes by collecting information from more sources. Theoretically, at least, two engineers with identical field data should arrive at similar conclusions using these classification schemes.

One current school of thought in tunnel design advocates the philosophy that the behavior of an underground excavation is governed by the interaction between the mass and support system. The analyses described in this chapter had as their basic goal the multiple task of satisfying current thought on tunnel behavior while at the same time attempting to exhibit either verification or total nonagreement with the results predicted by the empirical methods.

The method chosen to attack this problem was to determine the ground reaction curves or support-deflection behavior of numerous jointed mass/excavation configurations. In this manner it was hoped to demonstrate that the Distinct Element model solutions would always predict support pressures that were significantly lower than those calculated by the empirical methods, since the predictions of these methods are based upon

supporting the total dead weight of a specified volume of rock. For the basic geometry selected for the study, the weight of the material for which it is kinematically possible, neglecting any supporting effects, to move into the excavation, and thus load the supports is easily calculated. It was expected that this potential ultimate roof load would provide a rarely attained upper limit to the necessary value of support resistance indicated by the analyses.

Both of these assumptions were found to be incorrect; in fact, the data indicate that the value for which the supports should be designed is given by the potential ultimate roof load. While this value is typically noticeably smaller than the support loads predicted by the empirical design schemes, there is not enough of a difference to conclude that it has been demonstrated that the use of the empirical methods results in an overdesign.

To understand the reason for the similarity of results, the characterization of the joints must be examined. The joints used at the present time in the Distinct Element method are smooth planar structures which have strength only through frictional resistance. The joints do not possess cohesion. Cohesive resistance is more significant in the initial strength of a rock mass than in determining the failing behavior. Not much is lost in the analyses of failing rock masses if no cohesion is assumed. The joints also are not characterized by dilatancy. The dilatancy properties of real joints contribute additional strength through volume increase

as shearing occurs. Neglecting the dilatancy of the joints must result in a conservative estimate of the strength. Additionally, in real excavations there is another dilatancy caused by the volume of rock surrounding an excavation moving radially inward. This mass dilatancy also acts to increase the normal force acting on the joints and thus increase the mass strength. The Distinct Element modeled geometries were designed so that only roof deflections were possible and thus neglected this mass dilatancy.

Another limitation imposed upon the analyses described in this chapter is concerned with the joint stiffness. In order that the program could be implemented on a mini-computer, many simplifications needed to be made; one of these was the use of "integer" arithmetic with the burden of watching the signs and decimal points placed upon the programmer (Cundall, 1974). One significant consequence of this was that the joint stiffness turned out to be a function of the problem size. The range of joint stiffness that could be investigated was thus limited. The approximation of the horizontal stress field as a constant load would negate the effects of varying the joint stiffness in any case.

It must be emphasized that the approximations just described are not a consequence of the Distinct Element formulation, but of the mini-computer configuration of the program. These approximations would not need to be made if the program ran in an environment of larger memory on a computer possessing a floating point processor.

The implication of the results presented in this chapter can thus be interpreted in one of two ways. By neglecting dilatancy,

a correlation was found between the required support force and the potential ultimate roof load. This support force was also found to correlate fairly well with the empirical methods particularly those of Stini and Cording et al. If it can be inferred that the failure to incorporate the dilatancy properties of real joints in the analysis leads to a value of the mass strength that is too low, then it can be concluded that the potential ultimate roof load and thus the empirical methods represent a conservative value of design load.

The second interpretation also follows from the properties of the joints. It is reasonable to expect that the dilatancy properties of joints would play a minor role in situations of relatively low stress. It can thus be concluded that dimensioning the supports to resist the potential ultimate roof load, or using one of the empirical schemes should give the best results in problems involving low stresses.

# CHAPTER VI

## SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FURTHER DEVELOPMENT

Before summarizing the results of this investigation, it is imperative that a few sentences be devoted to defining the "ground rules", so to speak, which must govern the discussion which follows immediately. The limitations placed upon joint behavior cannot be overemphasized. The joints within the models utilized in this study were smooth and planar; any shear resisting strength of the joint was due solely to frictional resistance developing as sliding occurred. The joints did not possess cohesive strength; as the cohesive properties are more important in determining the initial strength of the mass, it was felt that little was lost by modeling failing, jointed masses by surfaces having no cohesive strength. The same cannot be said for the fact that the joints utilized did not possess dilatancy characteristics. It is possible that the inclusion of joint dilatancy could significantly affect the resultant mass strength and thus the outcome of many of the analyses reported in this dissertation.

A complete summary of the results of each section is presented at the end of that section; the summary of results presented here will thus be relatively brief.

One of the main goals of this dissertation was to demonstrate that the behavior of jointed rock as predicted by the Distinct Element method was realistic. The approach taken to demonstrate the

validity of the Distinct Element method was based upon comparison to solutions commonly used to describe the behavior of jointed rock masses. The majority of the solution methods chosen for comparison were based upon Limit Equilibrium principles; a basis for selection for comparison was a subjective criterion of how well the solution described the behavior of the model. Thus those solutions selected for comparison are typically simple and the resultant behavior can be intuitively predicted. In all of the comparisons presented in Chapter 3 as well as others presented throughout the remainder of the dissertation, the Distinct Element calculated behavior was seen to correlate quite well with the theoretical solutions.

The second portion of the dissertation described the results of numerous analyses of the behavior of jointed masses by use of the Distinct Element method. The goals of these analyses were to determine those parameters to which the stability of an excavation in jointed rock was most sensitive and to investigate the effects of support interaction in jointed media in an attempt to determine if a rational basis existed for the continued use of empirical design schemes.

The subjects of Chapter 4 were an investigation of the force distributions surrounding excavations in jointed rock masses and an examination of the stability of unsupported excavations. The topics were approached through numerous models in which the input parameters were varied and the resultant behavior of the model observed. The behavior of the models was illustrated by means of

contact force distributions and block displacements plotted on the graphics terminal. The behavior of the models was seen to be governed by force transfer due to the development of arches following block rotations. The stability of an excavation was seen to be sensitive to the horizontal force, the joint friction coefficient and the spacing of the vertical joints. A linear arch analysis neglecting crushing of the blocks and lateral stiffness of the abutments was compared to the behavior as observed by use of the Distinct Element method. Good agreement between theory and observation were noted for single layer models. The theory did not account for the presence of additional shear resistance available in multilayer models and thus there was a poor correlation between theory and observed data.

The investigations described in Chapter 5, on the other hand, were concerned with the behavior of excavations which required externally applied support to maintain stability. The investigations were concerned with the interaction between the supports and the jointed mass and formed the basis for a comparison with different empirical support load prediction schemes. The required supporting force as predicted by the Distinct Element method was obtained through the use of ground reaction curves. These Distinct Element calculated support forces were then compared to the support forces predicted by the empirical methods. Incorporated within this comparison was actual support design data for several underground excavations.

The methods which best describe the combined Distinct Element calculated data and design data were seen to be the methods of Cording et al. and the method based upon the potential ultimate roof load described in Chapter 5. It should come as no surprise that Cording et al.'s method fits their data; it is significant that Cording et al's method fits the Distinct Element calculated data and that the support load predictions based upon analyses performed using the Distinct Element method fit the field data as well as is seen. As was noted in the summary of Chapter 5, the incorporation of dilatancy behavior in the joints of the Distinct Element model could significantly alter the results of these comparisons.

The results of the analyses of excavations jointed masses suggest that the Distinct Element method deserves consideration for use in the design of underground excavations. There is not meant to be an implication that all of the information needed to specify a support system for an underground excavation can be obtained by an application of the Distinct Element method. It is only suggested that the Distinct Element method be used as one of the many tools used in the design of an underground excavation.

It is tempting to conclude that a viable design technique would be to analyze a given problem neglecting the dilatant properties of the joints; using this approach it might be argued that a safety factor would be built into the analysis. However, until the joint dilatancy properties are fully understood it must be recognized that there would be a good deal of uncertainty as to whether or not the safety factor would be one or ten or even one hundred.

The data which should routinely be collected during a preliminary site investigation can be utilized in the Distinct Element method to provide preliminary design information. This data would likely include preliminary information on joint spacing, orientation and condition as well as estimates of the horizontal stress state. Using the Distinct Element method, it could quickly be determined if the excavation would be stable or require light or heavy supports. Variations of these input parameters would result in a good idea of how sensitive the excavation stability would be to errors in the assumed values of the input parameters. This analysis could be continuously updated as data from exploratory drilling become available and further refinements could accompany the excavation progress.

This type of design technique is not limited to tunnels; the same data and same procedure are equally applicable to the analysis of slope problems or foundation problems.

These are several reasons that suggest that the method just described is particularly applicable to a class of problems which could be best described as low stress problems. The very nature of the present formulation of the Distinct Element method makes it imperative that it only be applied to problems where the behavior of the mass is controlled by the jointing; this is a characteristic of problems that are near or at the surface. A low stress problem also exists where the frictional resistance of the joints is very low, perhaps due to the presence of clay seams. The investigations

described in Chapter 4 indicated that the material within the zone of potential finite displacement also typically fit the requirements of low stress behavior, although this behavior can be prevented by the presence of high horizontal stresses.

The conclusions to this dissertation must also address the problems encountered due to the mini-computer configuration of the present version of the Distinct Element program. It should be noted from the outset that these are not criticisms of the Distinct Element method itself, but of the equipment upon which the program used in this study presently runs. Foremost of these criticisms must be the time required for a problem solution. The relatively slow computational speed of the mini-computer coupled with the lack of a floating point processor often led to problem solution times which could only be tolerated by someone working toward a Ph.D. Computational times approximately one-twentieth of those encountered during this study could easily be realized on a more powerful computer. However, lost by this implementation would be one of the most powerful capabilities of the Distinct Element program. The insight into the behavior of a jointed mass gained by examining contact force distributions at each time step is often quite revealing. This can realistically only be done on a dedicated computer.

The amount of computing time required and the limited memory size of the mini-computer also acted to limit the size of the problem that could be investigated. These limitations often resulted in simplified models such as those used to determine the ground

reaction curves presented in Chapter 5. It was noted in Chapter 5 that the idealizations could have masked an important behavior response due to inward movement of the side walls accompanying the roof deflections. This question cannot be resolved until the Distinct Element method is configured on a system possessing a greater amount of memory.

One of the underlying goals of this dissertation was concerned with the utilization of a computer interactive graphics approach to an engineering problem. One particular phase of the project was concerned with developing the graphic interaction capabilities of the present version of the Distinct Element program to the point where an untrained user, particularly one having minimal familiarity with computing techniques, could sit down and use the program to solve simple problems. The solution of this problem was to incorporate a great deal of explanatory material within the program. It is difficult to assess the success of this portion of the project in other than a subjective manner. It did, however, seem as though the majority of those using the program for the first time encountered little difficulty.

Also within the defined goals of this dissertation was the problem of developing a proper perspective as to the applicability of the Distinct Element method. The conclusions drawn are subjective and incorporate material not described in this dissertation. The class of problems most suitable to analyses by the Distinct Element method is characterized by relatively low stress conditions and behavior which is joint controlled. Typical examples of problems

meeting these requirements involve slope stability, shallow excavations and foundation behavior. The degree of unconfinement characteristic of these problems ensures that the behavior of these types of problems will be joint controlled. However, the possibility of fracturing of blocks due to local stress concentrations must not be overlooked. It is reasonable therefore to use the analysis obtained by the Distinct Element method in conjunction with an elastic analysis used to determine zones of stress concentration and thus potential fracture. These potential fracture planes can then be incorporated within the Distinct Element method to determine any possible effect.

The dividing line between low stress problems and high stress problems is not clearly defined. It has been noted that the zone of material immediately adjacent to an excavation is under relatively low stress conditions; due to the action of the ground arch the material surrounding the destressed zone experiences much higher stresses. The logical solutions to problems of this type would be either a coupled elastic-Distinct Element program or a modified Distinct Element program which incorporated elastic rather than rigid blocks.

It is clear from the work typified by Daemen (1975) that highly fractured rock can be modeled by a continuum representation incorporating residual strength properties. It was not possible within the context of the present study, given the limited number of blocks, to determine that point at which the behavior of broken rock ceases to be governed by the directionality imposed by the

joints and can thus be represented as isotropic. The work described by Bray (1966) does, however, furnish at least a guideline. Bray examined the behavior of jointed masses subjected to an arbitrarily oriented stress field. His results indicated that six independently oriented joint sets were required before the behavior of a jointed mass approximated that of a granular isotropic material. The implication here is that if the material is highly fractured or if the stress conditions are sufficient to fracture the rock it is probably best to adopt a continuum approach.

The research undertaken for this dissertation indicated several areas where further development of the program could be beneficial, and suggested an area of research that could prove to be most rewarding.

The first steps that need to be taken in any further development of the Distinct Element program require faster computational times and a significantly larger computer memory. The results of Chapter 5 were based upon idealized geometries; the typical amount of mini-computer time required to generate one of the ground reaction curves often exceeded two days. This amount of time simply cannot be tolerated if the program is to be accepted as a design tool. The shortcomings of the limited number of blocks were also indicated. The solution to both of these problems is the implementation of the model on a larger, faster computer.

The most promising areas of further research identified by this dissertation are concerned with the continued investigation of the behavior of excavations in jointed rock. Foremost of these should

logically be the incorporation of dilatant behavior of the joints. Additionally, an implementation on a larger computer would allow more blocks per problem and thus a more accurate representation of an underground excavation. This implementation would also allow the incorporation of a stiffness representation of a support system. This would also lead to a better description of the support system/ mass interaction. It is still felt that, if at all possible, this implementation should take place on a dedicated computer.

The area of research not covered by this investigation which holds promise for a future study is a detailed comparison of the results of observations and careful measurements of physical models and comparable model behavior calculated by the Distinct Element method. This research could form the basis for the incorporation of dilatant behavior in the Distinct Element method as well as providing additional verification of the Distinct Element method through carefully controlled physical testing. In fact, it is easy to visualize a research program that is highly complementary in nature, utilizing a sort of "feedback" system. The Distinct Element method would be useful in the interpretation of the observed data from the physical model while at the same time, the physical model would help to refine the equations used in the Distinct Element formulation.

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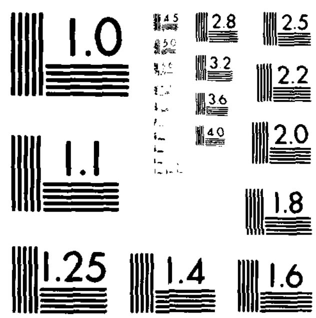


MICROCOPY RESOLUTION TEST CHART

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# APPENDIX A

## THE DISTINCT ELEMENT METHOD

The Distinct Element method is a computer model described by Cundall (1971a) that simulates the behavior of assemblages of rock blocks. The version of the program described by Cundall (1974) forms the basis for the work described in this thesis. Significant features of the program described by Cundall (1974) include arbitrary block shapes, unlimited block displacements and rotations, and a high degree of user interaction. The interaction requires a dedicated computer and centers around a graphic terminal with a cross-hair cursor input capability. The system enables the user to draw a picture of the problem on the terminal and watch the subsequent movement of the blocks as gravity and other loads are applied.

A very thorough presentation of the algorithms implemented in the program, as well as a description of the required hardware, is given by Cundall (1974). The purpose of this appendix is to briefly summarize Cundall's description of the program and note the significant additions to the formulation. Little would be gained by repeating Cundall's descriptions since his report is readily available.

The calculation cycle used in the program is similar to the one used in most explicit finite difference calculation schemes. Forces arise due to the deformations that occur at corner-to-edge contact points. In each time step of the iteration the incremental shear and normal displacements for a given contact point are calculated using the incremental translational and rotational

displacements of the two blocks in contact. The new shear and normal forces acting on the blocks are then calculated from force-displacement relationships. All of the contact forces for a given block are then resolved into an equipollent set of forces including a moment acting on the block.

The force and moment sums acting on each block are used to compute translational and rotational accelerations for the block. The accelerations are integrated numerically to obtain block velocities which are then integrated to give the block displacements. With this new set of block displacements the iteration cycle can begin again. Note that if the force and moment sums acting on a block are zero, there will be no acceleration of the block; this is precisely how the program models an equilibrium state.

Before the displacements and accelerations of the blocks can be calculated, however, some method of defining the block geometries must be implemented. The blocks could be treated as "elements" related to defined nodal points as is done in conventional Finite Element analyses. The input would thus consist of numerous cards containing nodal point and element data; anyone who has attempted this to define a mesh for a Finite Element analysis is acutely aware of the frustration that results from trying to "debug" such a mesh. The approach adopted by Cundall (1974) and implemented in the program used for the research described in this dissertation overcomes the difficulties associated with mesh generation. The actual rock mass geometry, as defined by the jointing, is drawn on the screen of the CRT. All calculations necessary to determine

the significant coordinates are thus performed by the program. The structure of the program is governed by the size limitations imposed by the mini-computer; the actual program consists of three overlays which correspond to the three main calculation phases of the program.

Phase 1 of the program governs the interactive dialog by which the lines defining the block geometry are created. A flow chart for this section of the program is given by Cundall (1974); the flow chart is essentially valid for the present configuration of the program. Care was taken so that the changes to Phase 1, which will be described presently, did not alter the program sequence or execution.

The two main changes made in the Phase 1 section of the program are concerned with the format of the data input and the storage and subsequent retrieval of data files. Whereas the initial version of the program used only the cross-hair cursor of the CRT for input, the present version of the program uses a graphic tablet ("digitizer") and a numeric input scheme as well. The three routines are virtually identical and, in fact, use only one set of coding. Whichever routine is active at a given time is noted by the value of the variable KODE: KODE = -1 signifies that the numeric input routine is selected; KODE = 1 signifies that the graphic tablet is in use; and, KODE = 0 signifies that the cross-hair cursor is being used for input. All three input methods may be used for a single problem. Potential users wishing to implement the modified version of the program need only supply software for the graphic tablet (Subroutine DIGIT). It should be noted that the numeric input routine contains a scale factor. In this manner, actual field

coordinates may be used as input, and divided so that they meet the program requirements (see Cundall, 1974).

The second major change in the Phase 1 program enables users to store data files consisting of line segments and coordinate data. To do this, the common blocks are written to or read from the Linc tape units. The operation is straight forward; line 57 of the program (see Appendix C) LIST (3) = 13286 is simply a "password" to prevent garbage from being read as a data file.

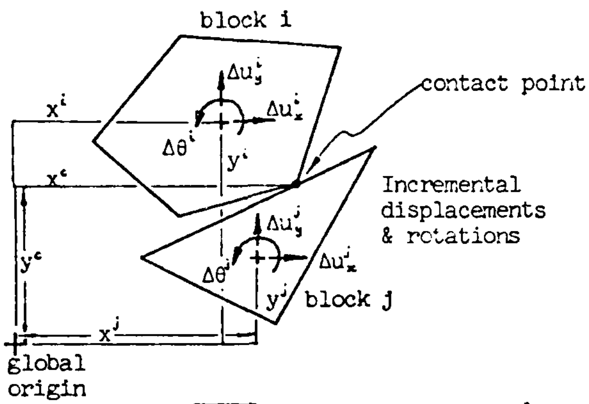
The second overlay, Phase 2, is unchanged from Cundall's (1974) original listing. This is the routine that scans the line segments created in Phase 1 of the program and converts the line segments to closed areas. A flow chart for this routine is presented by Cundall (1974).

The first two overlays of the program are written in Fortran; to conserve memory, the third overlay is written in Data General assembly language. The only serious drawback caused by this is that the present version of the program will only run on a Data General computer.

Most of the changes made to the program were concerned with the third overlay, Phase 3. This section of the program contains the coding necessary to compute the block accelerations and displacements. Detailed descriptions of the modifications will be noted in the descriptive summary of the Phase 3 subroutines to be presented shortly; the main calculation cycle, however, remains essentially unchanged.

The equations used in the main calculation cycle are summarized

on this and the following pages and are taken directly from Cundall (1974).



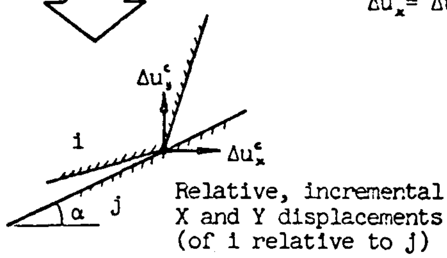

$(x^i,y^i)$ = global co-ordinates of block i centroid

$(x^j,y^j)$ = global co-ordinates of block j centroid

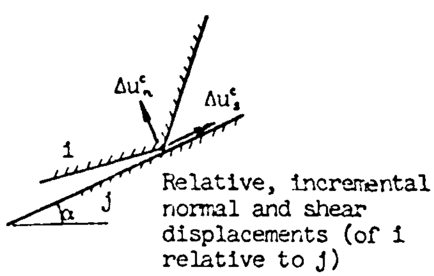
$(x^c,y^c)$ = global co-ordinates of contact point c

Note: All forces, displacements and angles are shown acting in the positive direction.

$$\left.\begin{aligned}\Delta u_y^c &= \Delta u_y^i - \Delta u_y^j + \Delta\theta^i(x^c - x^i) - \Delta\theta^j(x^c - x^j)\\ \Delta u_x^c &= \Delta u_x^i - \Delta u_x^j - \Delta\theta^i(y^c - y^i) + \Delta\theta^j(y^c - y^j)\end{aligned}\right\}\quad(1)$$




$$\left.\begin{aligned}\Delta u_s^c &= \Delta u_x^c\cos\alpha + \Delta u_y^c\sin\alpha\\ \Delta u_n^c &= \Delta u_y^c\cos\alpha - \Delta u_x^c\sin\alpha\end{aligned}\right\}\quad(2)$$

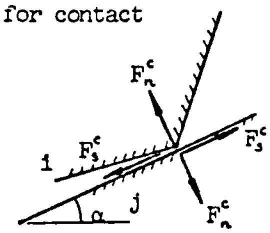


Equations (continued)

$$F_n^c := F_n^c - \Delta u_n^c . k_n \quad *$$
$$F_s^c := F_s^c + \Delta u_s^c . k_s$$
$$\left.\begin{aligned} D_n^c &= -\Delta u_n^c . K_n \\ D_s^c &= \Delta u_s^c . K_s \end{aligned}\right\}$$ (Dashpot forces, D act in same manner as F forces)

The above equations are subject to the following conditions:

Shear and normal forces for contact




→ If $F_n^c < 0$ , (3)

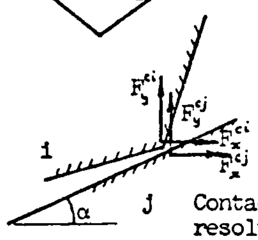
set $\left.\begin{aligned} F_n^c &= 0 , D_n^c = 0 \\ F_s^c &= 0 , D_s^c = 0 \end{aligned}\right\}$ (no-tension)

→ If $|F_s^c| > \mu . F_n$,

set $F_s^c := \mu . F_n^c . \mathrm{sign}[F_s^c]$ (friction law)
$D_s^c = 0$ (no damping when sliding)

(where: $k_n$ = normal stiffness,
$k_s$ = shear stiffness,
$K_n$ = normal dashpot constant,
$K_s$ = shear dashpot constant.)

$$\left.\begin{aligned} F_y^{cj} &= (F_s^c + D_s^c)\sin\alpha - (F_n^c + D_n^c)\cos\alpha \\ F_x^{cj} &= (F_s^c + D_s^c)\cos\alpha + (F_n^c + D_n^c)\sin\alpha \\ F_y^{ci} &= -F_y^{cj} \\ F_x^{ci} &= -F_x^{cj} \end{aligned}\right\} (4)$$



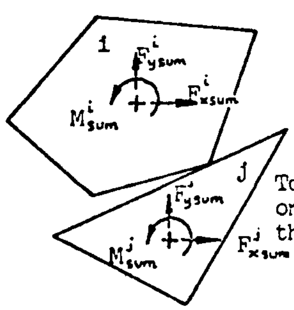

Contact forces resolved into global X - Y directions

$\left.\begin{aligned} F_{xload}^i &= \text{applied x load} \\ F_{yload}^i &= \text{applied y load} \\ F_{ygrav}^i &= \text{gravity force} \end{aligned}\right\}$ body forces

$$\left.\begin{aligned} F_{xsum}^i &= \textstyle\sum_c F_x^{ci} + F_{xload}^i \\ F_{ysum}^i &= \textstyle\sum_c F_y^{ci} + F_{yload}^i + F_{ygrav}^i \\ M_{sum}^i &= \textstyle\sum_c \{F_y^{ci}(x^c - x^i) - F_x^{ci}(y^c - y^i)\} \end{aligned}\right\} (5) \; ①$$

Note: $\sum_c$ means the summation over all contact points for block i

Exactly similar equations are used for block j

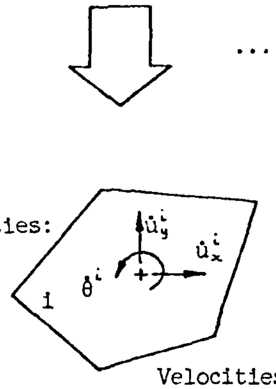



Total forces and moments acting on block i found from the sum of the contributions of each contact.

* The symbol := means "replaced by"

① The formulation of equation 5 differs slightly when joint water pressure is present (see page A-22).

Equations (continued)

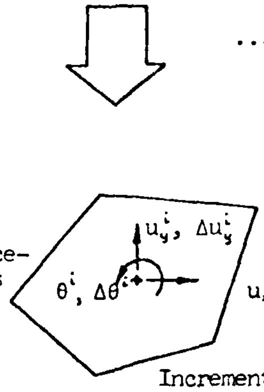



$$\left.\begin{aligned} \dot{u}_y^i &:= \dot{u}_y^i + \frac{F_{ysum}^i \cdot \Delta t}{m^i} \\ \dot{u}_x^i &:= \dot{u}_x^i + \frac{F_{xsum}^i \cdot \Delta t}{m^i} \\ \dot{\theta}^i &:= \dot{\theta}^i + \frac{M_{sum}^i \cdot \Delta t}{I^i} \end{aligned}\right\} \quad (6)$$

Similarly for block j

( $\Delta t$ = time increment;
$m^i$ = mass of block i;
$I^i$ = moment of inertia, block i.)

Velocities are derived from forces, by numerical integration




$$\left.\begin{aligned} \Delta u_y^i &= \dot{u}_y^i \cdot \Delta t \\ \Delta u_x^i &= \dot{u}_x^i \cdot \Delta t \\ \Delta \theta^i &= \dot{\theta}^i \cdot \Delta t \\ u_y^i &:= u_y^i + \Delta u_y^i \\ u_x^i &:= u_x^i + \Delta u_x^i \\ \theta^i &:= \theta^i + \Delta \theta^i \end{aligned}\right\} \quad (7)$$

Similarly for block j

Incremental displacements and absolute displacements derived from velocities.

At this point the calculation cycle is complete since the incremental displacements needed by equation 1 on page A-5 have been calculated. A complete discussion of the relationships used in equations 1 - 7 is given by Cundall (1974). The algorithms used to derive the coordinates and angles used by equations 1 and 2 are also presented.

As a prerequisite to the discussion of the Phase 3 subroutines, a brief discussion of the data structures is necessary. The problem of unlimited block movement and the potential for any given block to contact any other block requires an efficient scheme of memory management. Simple sequential arrays are not sufficient for the task at hand as it requires that the words in the memory be subject to additions and deletions of data while at the same time the amount of unused memory, memory reshuffling and processor time must be kept to a minimum. The solution implemented by Cundall to alleviate the difficulties of handling large, sparse data arrays was borrowed from the techniques of manipulating information structures by computer. The data structures rely heavily on the techniques of list processing whereby the data is stored in short lists in arbitrary computer memory locations with one word of the list containing information sufficient to locate subsequent data. The entirety of the data can thus be imagined to be one long list comprised of several short lists strung together through the memory. The reader who requires exact details concerning the implementation of the list processing techniques is advised to consult Cundall (1974) pages 62 - 72. All that will be presented herein is a brief overview of the list processing implementation and a description of the format of the data structures used in the present formulation of the program.

The storage requirements for a given block model due to the problem of allowing any block to touch any other block are overcome by a list scheme. All block corners are classified into coarse

boxes covering the screen area. When the program needs to know if a given edge is near any block corners, it is only necessary to scan the area delimited by those boxes encompassing the edge. As the blocks move as a result of forces acting on them, their corners are reclassified into new boxes if necessary. This boxing scheme turns out to be very efficient as only a small amount of computer time is required.

It is impossible to allocate sufficient memory space for all possible block to block contacts - the space required is far too great. The only viable solution is a method to allocate memory as it is needed by the formation of a new contact and return the memory to a pool of available memory when it is no longer needed. A scheme of linked memory allocation provides such a solution and is implemented in the Distinct Element program.

In the program a fixed group of words is reserved as a set of pointers; each word corresponds to a given block. Each pointer contains the address of the start of a linked list of all contacts for the block associated with that pointer. Another list is used to store all of the memory which became "dead" once a contact was broken. When a new contact is detected by the program the program first checks the list of dead contact space. If space exists it is used, otherwise, previously unused memory at the high end of core is allocated. The following pages describe in detail how the data is organized in the computer memory. The first page following shows a total memory map illustrating the four main parts of the memory. These are:

a) the program

b) the sets of data pertaining to each block

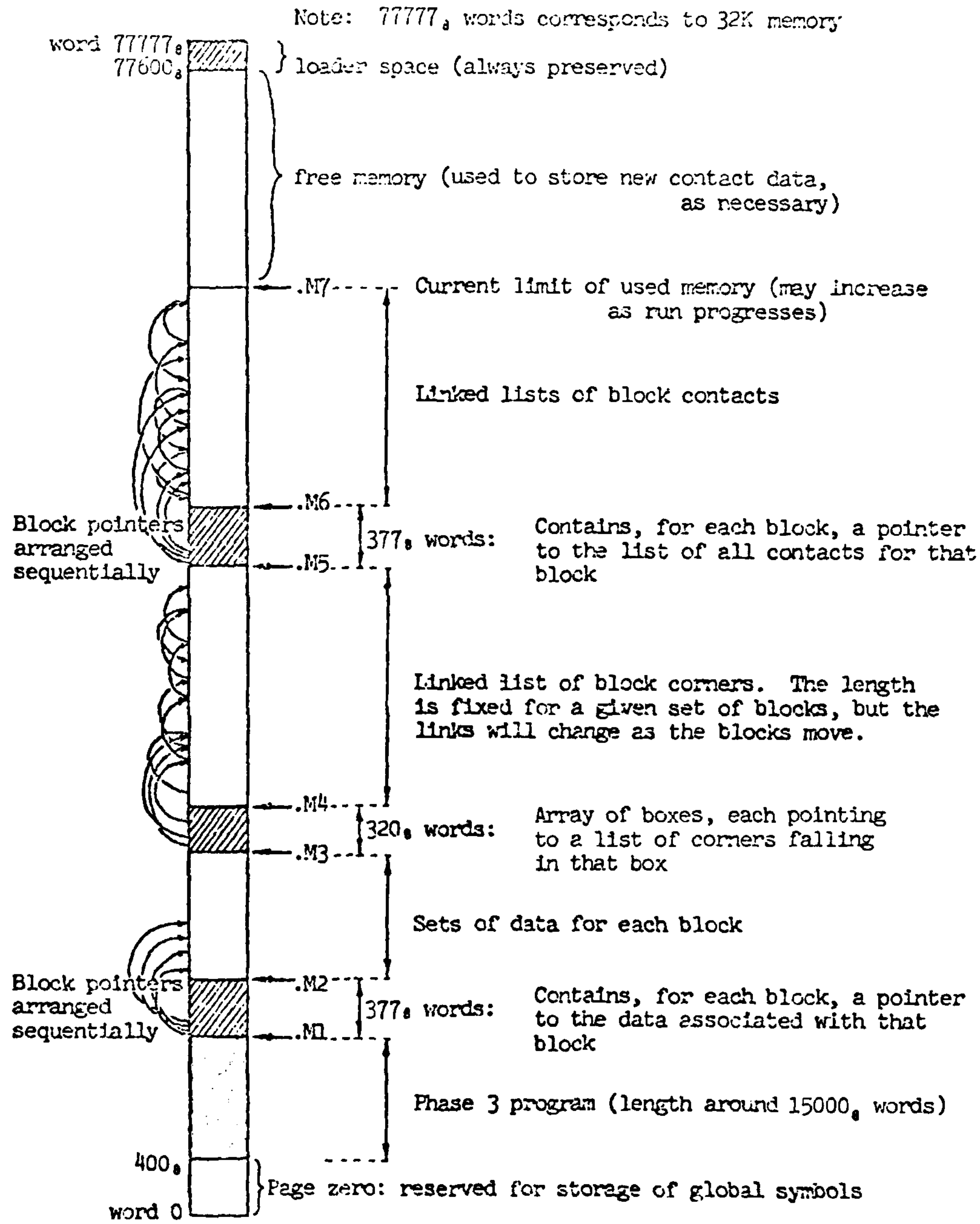
c) the pointers and data necessary for the "boxing" scheme, and

d) the data sets and pointers pertaining to the contact between blocks

The subsequent pages illustrate expanded forms of groups b, c, and d to show in detail the structure of each list.

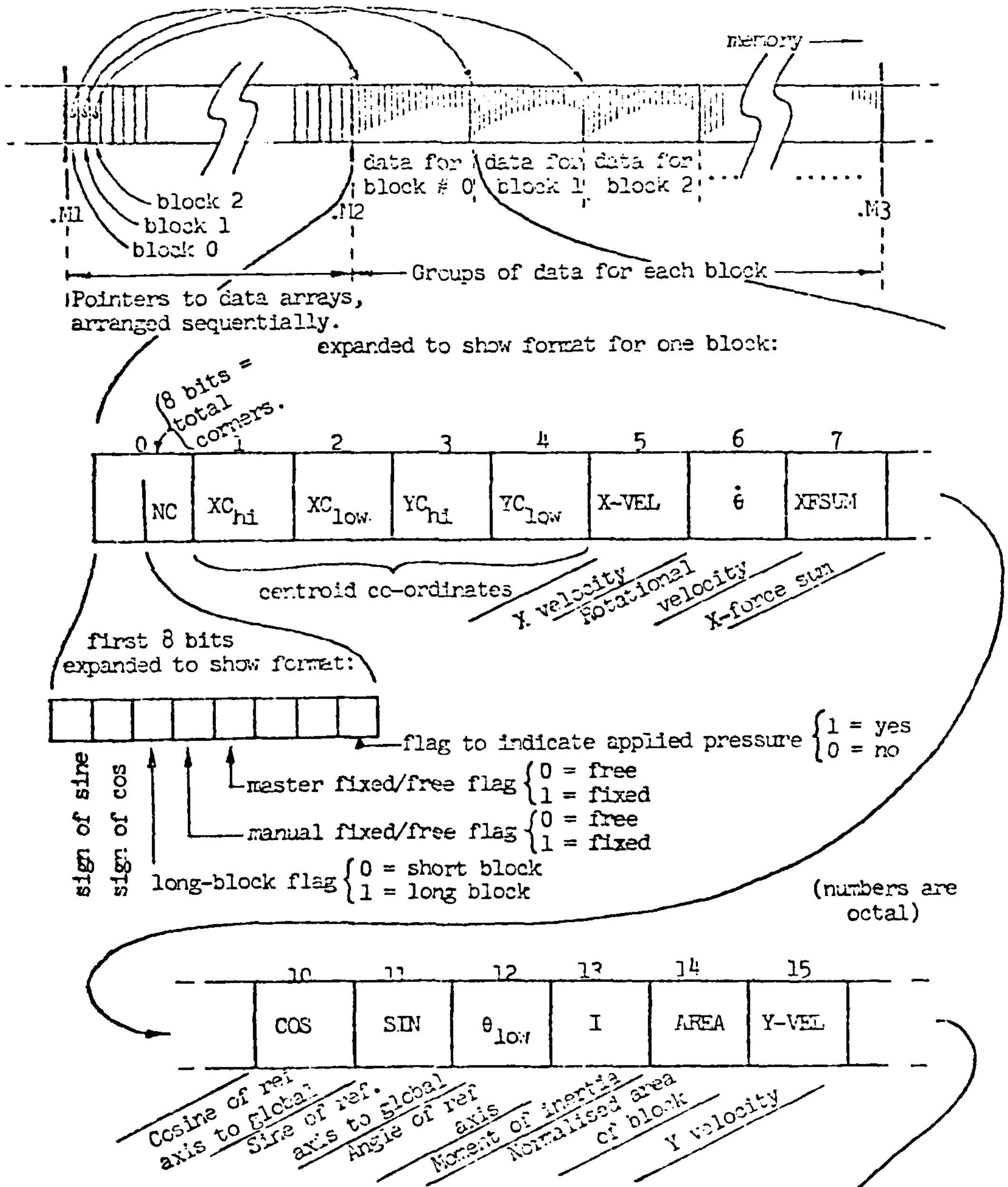
The present formulation of the program utilizes another linking scheme to store the data pertinent to applied joint water pressures when they exist. The format of data lists used in this scheme is also illustrated. There are two other linked lists threaded through the memory that must be mentioned; these are the "empty" lists used to reference previously used memory space that is now free for re-use. Memory is made available whenever a block contact is broken or when a pressure segment is deactivated. The two empty lists and the joint pressure lists are referenced by global memory pointers and make use of whatever memory is available. Adding or reclaiming a group of words from the empty lists is simply a matter of reshuffling the link bits and is illustrated by Cundall (1974).

Total memory map for Phase 3



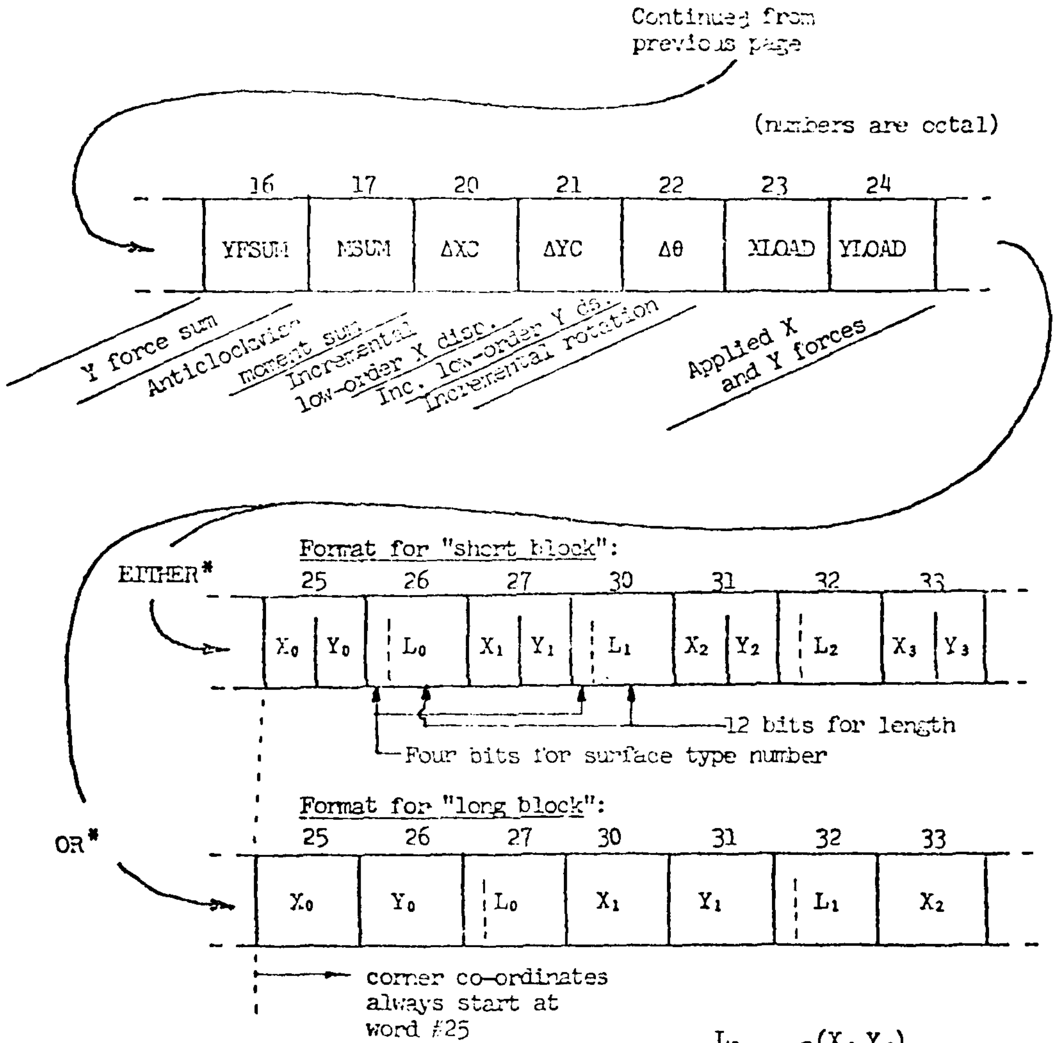

Note: .M1, .M2 etc are the global symbols that refer to the pointers to the memory locations shown

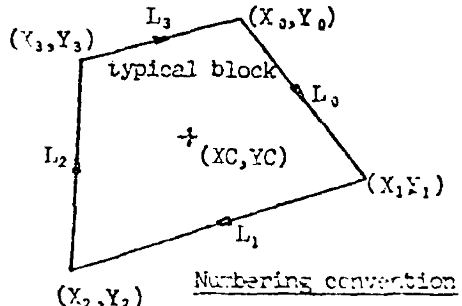
Format of data arrays for blocks




COS and SIN are stored as unsigned fractions (<1)
(i.e. 1·0 is stored as $177777_8$)

continued on next page...



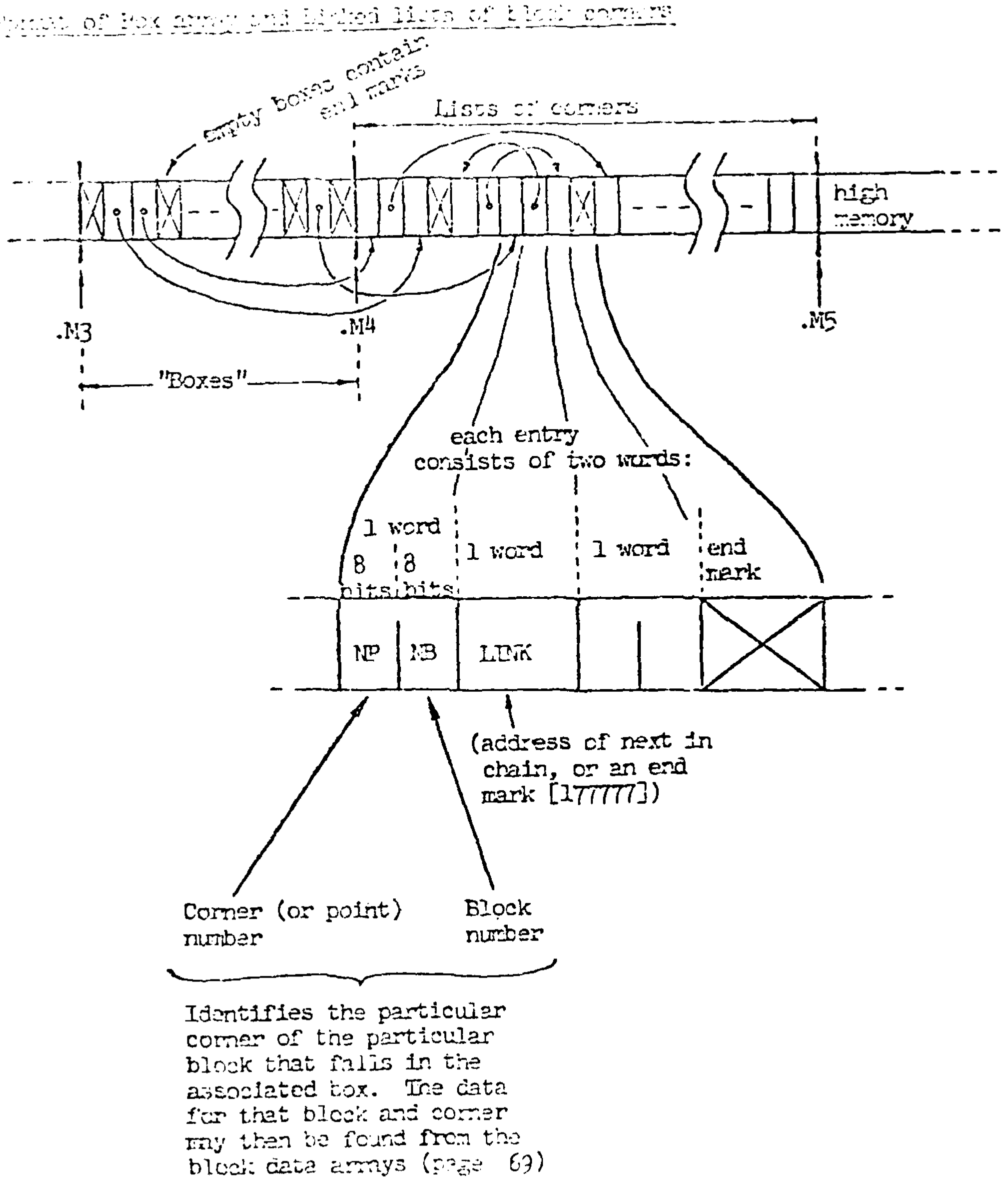

Numbering convention

($L_i$ are lengths)

$(X_i, Y_i)$ are local co-ordinates

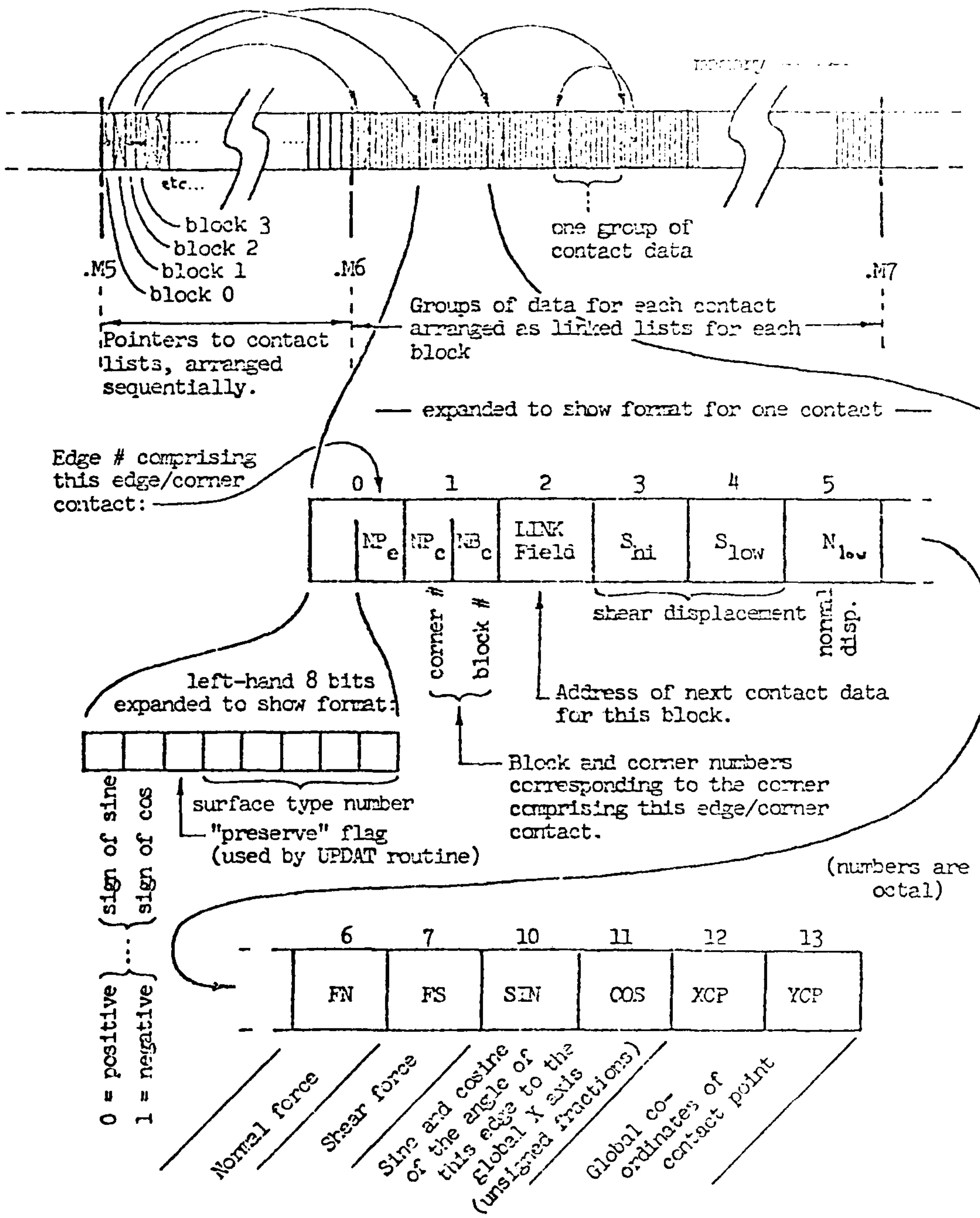
* NOTE: If any $|X_i|$ or $|Y_i|$ is greater than $127_{10}$, the block is classified as a LONG BLOCK, and the second format shown is used. This is to save memory, as only a few blocks will be long.

Format of Box array and Linked lists of block corners



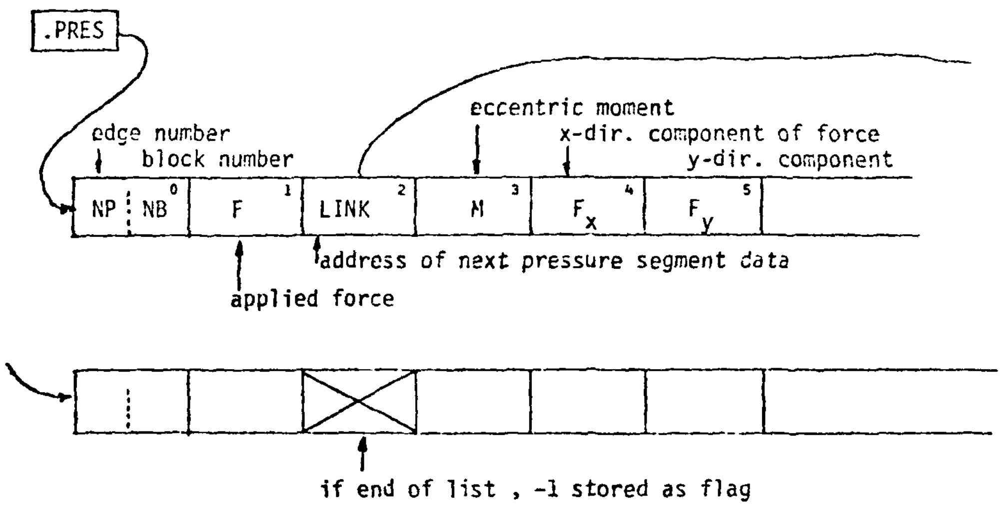

Note: .M3 , .M4 & .M5 are the global symbols (program names)
for the pointers to the groups of memory shown

Format for contact data lists, and associated pointers

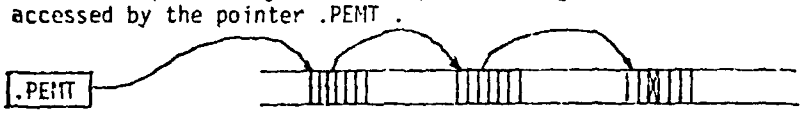


Format of Linked Lists of Pressure Segment Data

if no pressure segments exist, .PRES = -1




The empty list of pressure segments strings together groups of six words which were previously active as pressure segment data lists. It is accessed by the pointer .PEMT .




The empty list of contact data has a similar form but the list groups are $13_8$ words long. It is accessed by the pointer .EMPT .

With this preliminary information in mind, a brief discussion of each of the subroutines of Phase 3 may now be presented. The logic of the subroutines is straight forward and due to the number of comments interspersed in the listing, there seems to be little need to present flow charts for the programs. The brievity of the discussion is justified by the fact that Cundall (1974) has adequately described the original versions of the subroutines. The descriptions presented herein are thus primarily concerned with the modifications made to the program.

Subroutine TRANS

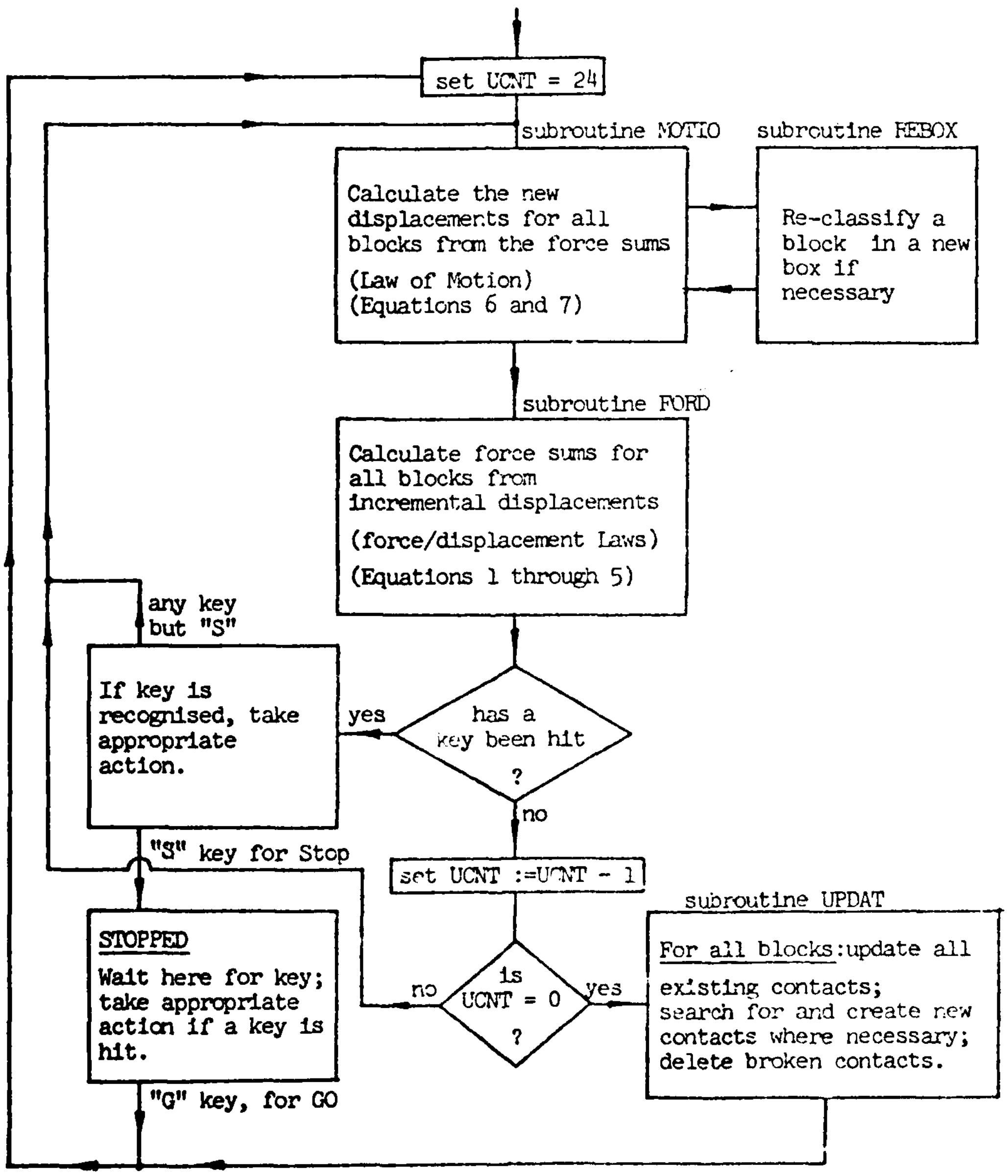
The purpose of TRANS is to translate the Fortran data arrays into the Phase 3 format illustrated on pages A-12 and A-13. It is the first subroutine to be executed in Phase 3 and is only used once. The program originally (Cundall, 1974) was overwritten by the data input routine, but this is no longer so. Additionally, TRANS classifies all of the block corners into boxes utilizing the format illustrated on page A-14; Cundall outlines the procedure for accomplishing this.

The changes made to TRANS are minor and are outlined in the following sentences. The initial program version was implemented for a specific memory size; the present version determines the size of its environment and adjusts itself accordingly. The routine determines the locations of the Fortran common blocks and sets several pointers. The memory sizing routine works for all physical

configurations except 32K words; for this memory size the common block locations are displaced by one word. For this reason variable IY is dimensioned as 513 only in Phase 3. This juggling is not necessary for other memory sizes and may not be necessary for other operating software.

Subroutine CONTR

The next routine to be executed governs the main control loop; subroutine CONTR also monitors the keyboard. The logic of the program is unchanged from Cundall (1974) but the fact that this routine embodies the main calculation cycle merits the presentation of a flow chart.



The overall logic of CONTR is straight forward and simply involves the evaluation, for each block in turn, of the sets of equations listed on pages A-5 through A-7.

The calculation of the displacements from the forces (subroutine MOTIO) involves the evaluation of equations 6 and 7 for each block. Accelerations derived from forces are integrated twice to give displacements. Gravity forces and any applied forces are added to the forces derived from block contracts. In this part of the calculation cycle the magnitude of the displacements are also monitored and if necessary, control is transferred to the routine that determines if any of the block corners need to be assigned to new boxes.

Having thus obtained incremental displacements for all blocks, the force/displacement laws (equations 1 through 5) are used to obtain contact forces.

The control routine also calls subroutine UPDAT every so often to update the coordinate data used in equations 1 through 7. UPDAT updates the sine and cosine of the edge in contact with a particular corner, as well as the global coordinates of the contact point. UPDAT also deletes broken contacts and searches for new ones.

The other function of subroutine CONTR is to monitor the keyboard and respond to keys hit by the user while the program is running or waiting. The program responds to the keys and modifies the sequential operation of the program. The function

of the individual keys is clearly explained in the listing of CONTR (Appendix C) as well as in Appendix B.

## Subroutine REBOX

As has been observed, the corner reboxing routine is called from MOTIO whenever a block is suspected of having moved sufficiently to need its corners reclassified into new boxes. The logic of the corner reboxing scheme is presented by Cundall (1974) and is unchanged in the present version of the program.

REBOX also updates the applied joint water pressures. The water pressures must act normal to the joint surface and do not dissipate as the blocks move. Any rotational movement of a block with an applied water pressure would lead to a change in the x and y components of the applied force. Subroutine REBOX updates this information whenever it is called for any block.

## Subroutine MOTIO

This subroutine evaluates equations 6 and 7 on page A-7 for all blocks except those having either the master or manual fix flags set. As noted earlier MOTIO also makes a decision when to call the reboxing routine to reclassify any block's corners into new boxes. A call to REBOX is triggered whenever the cumulative motion of any block exceeds one screen unit.

Subroutine FORD

This subroutine evaluates equations 1 through 5 on page A-5 and A-6 for each block in sequence. It accesses the data stored in the contact list associated with each block, and computes the force sums acting on that block. Equation 5 is the only equation of the main calculation cycle that is different than that presented by Cundall. It now contains terms to account for the presence of joint water pressure.

$$\begin{aligned} F^i_{xsum} &= \sum_c F^{ci}_x + F^i_{xload} + F^i_{xpres} \\ F^i_{ysum} &= \sum_c F^{ci}_y + F^i_{yload} + F^i_{ypres} + F^i_{ygrav} \\ M^i_{sum} &= \sum_c F^{ci}_y (x^c - x^i) - F^{ci}_x (y^c - y^i) + M_{pres} \end{aligned} \qquad (5)$$

Ford also contains numerous entry points that are primarily used for experimenting with the program. These entry points allow modification of block weights and the dynamic factors of the program.

Subroutine UPDAT

The subroutine UPDAT is called once every few iteration cycles to check for new contact points. UPDAT also updates coordinate data as required. The routine is unchanged from the original form; the description presented by Cundall is very complete and contains a flow chart of the subroutine.

Subroutine PONT

Subroutine PONT is used to calculate the global coordinates of a contact point from the local coordinates of that point. This is

done by a simple coordinate transform for a translated origin and rotated axes. The equations are: (see any book on analytic geometry)

$$XG = XC + XL.\cos\theta - YL.\sin\theta$$

$$YG = YC + XL.\sin\theta + YL.\cos\theta$$

where XL, YL = local coordinates

XG, YG = global coordinates

$\theta$ = angle of local system to global system

XC, YC = local origin (= block centroid)

Subroutines DISPL and TEK

With the exception of the contact vectors, which are generated by subroutine FORD, all screen plotting is managed by subroutine DISPL. Subroutine DISPL in turn calls TEK which is nothing more than the basic Tektronix supplied software package for mini-computers. Whereas Cundall's (1974) version of the program provided hard copy through digital plotting, the present hardware includes a Tektronix 4631 copier. Although DISPL will still drive a digital plotter, this feature is rarely used.

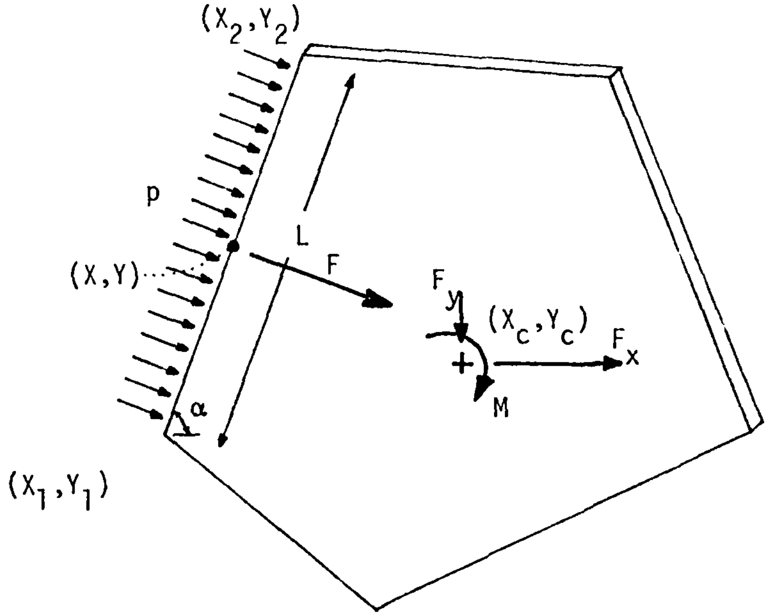
The remainder of the subroutines of Phase 3 are primarily used for various utility functions. No great detail will be expended on describing the main function of each routine. The subroutine listings (Appendix C) contain many comments that indicate how the functions are performed. The interested reader is directed to the listings.

Subroutine INPUT

The utility routines embodied in INPUT are primarily concerned with parameter specification and modification. Most significant of the functions are:

1) set up or modify the values of the ten different friction properties used by the program
2) input of applied pressures
3) numerical input of applied loads
4) set up of displacement control routine

The input of pressure segments deserves further attention. The presence of water in a joint tends to exert a force against the joint surfaces. For a single joint surface:




unit depth

1) $F = P * L * (1)$

2) $y_d = x_2 - x_1$

$x_d = y_2 - y_1$

3) $M = F\ (\sin\alpha\ (y_c - y) + \cos\alpha\ (x_c - x))$

or

$$M = \frac{F}{L}\ (y_d\ (y_c - y) + x_d\ (x_c - x))$$

F and M are calculated as soon as a pressure segment is defined and never varies with displacement. The x and y components of the force do vary with displacement and are updated in REBOX.

4) $F_x = F.\sin\alpha$

$F_y = - F.\cos\alpha$

The initial value of $F_x$ and $F_y$ is also calculated in REBOX.

Subroutine UTIL

Subroutine UTIL contains several utility programs. The entry points and their functions are:

1) .HITC - a routine to determine which block has the centroid corresponding to given x and y coordinates.

2) .PRN1 - output a single character to the teletype

3) .ALPH - sets the Tektronix to alpha mode

4) .PAGE - a routine to clear the Tektronix screen

5) .LENG - a routine to return the length of side NP of the block in question

6) .TYP - a routine to return the surface type number of a given edge

7) .SCAL - a routine to scale vector lengths

8) .IPRN - a binary to decimal conversion routine that prints a right justified integer in a given field length

9) .PRN2 - a routine to print a single character on the teletype - character is in ACØ

10) .MESS - a routine to print a message at a specific location on the screen

11) .AXIS - a routine to draw an axis with tick marks

12) .GETT - a routine to receive a character from the teletype

13) .DBIN - a decimal to binary conversion routine

14) .CHEK - checks if an ASC11 byte is a digit and reduces it to binary if it is

15) .WORD - a routine to get an alphanumeric string from the key board

Subroutine CYCLE

Subroutine CYCLE contains several additional utility routines. The entry points and their functions are:

1) .KET - a routine to set velocities to zero at a kinetic energy peak

2) .RSET - a routine to set the iteration cycle counter to zero

3) OPTIN - a routine to set options governing vector scale factors, automatic copy and automatic stop

4) .STEP - a routine to step the iteration cycle counter

5) .TPRN - a routine to print elapsed cycles

Subroutine HITS

Subroutine HITS checks all sides of all of the blocks to determine which edge of which block the coordinates x and y fall upon.

Subroutine LOADS

Subroutine LOADS allows all block weights to be multiplied or divided by an integer constant.

Subroutine MOVIT

The law of motion for displacement controlled blocks is embodied in subroutine MOVIT

Subroutine TAPE

Subroutine TAPE contains the standard Linc tape utilities. It also contains the coding for reading or writing save files in Phase 3, and performs the overlay to return to Phase 1.

# APPENDIX B

## USER MANUAL FOR DISTINCT ELEMENT PROGRAM

The information contained in this Appendix describes the operation of the configuration of the Distinct Element program used for this dissertation. The Appendix is arranged in such a way that each of the three operating phases is described in sequence, with comment interspersed as necessary. The comment following the third phase of the program is extensive and contains much information pertinent to the successful operation of the program.

During all three phases of operation the computer responds to user commands whenever a teletype key is struck. There are a lot of key commands to which the program will respond with appropriate action. Lists of these keys follow. Rather than memorizing the lists and attempting to implement them all at once, it is strongly suggested that the potential user familiarize himself first with those keys which are essential to the operation of the program. As the user becomes confident in the use of these keys through the running of simple examples, more keys can be added to his "working vocabulary".

Essential Keys

Phase 1 - 1, 2, E, P-2, rubout

Phase 2 - E, S, R, P-3

Phase 3 - G, D, F, C, Z, I (F), S

If a more detailed introduction to the use of the program is desired see Cundall (1974).

PHASE 1 - OPERATIVE KEYS, CURSOR DISPLAYED

1 - Key "1" is always used to define the first end of a line segment. Move the cross-hair cursor to the desired point and strike the key. The computer responds by drawing a "+" at the point indicated.

2 - Key "2" is always used to define the second end of a line segment. Move the cross-hair cursor to the desired point and strike the key. The computer responds by drawing a "+" at the indicated point and by drawing a line between the first and second end points of the desired line segment. The computer program was modified to recognize the fact that it is often desirable to draw connected line segments. Therefore, the program will respond to the "2" key following either a "1" key or a "2" key. In this case the program supplies the coordinates of the first endpoint of the line segment at the proper time by using the last input of the second end of a line segment.

E - Any individual line segment may be erased by placing the cross-hair cursor at any position on the line segment and typing the "E" key. A useful trick to make the drawing clearer is to create a line segment at the edge of the Tektronix screen and then erase it. When the remaining line segments are redrawn, the "+'s" at the ends of line segments are not redrawn.

rub-out All created line segments may be erased by typing the "rubout" key. When the "E" key is used to erase a line segment, the end points of that line are not removed from the point list.

These points can often impede the creation of a drawing. If a large number of line segments are to be erased, it is preferable to use the "rubout" key.

H - To make a hard copy of the Tektronix display type key "H" or strike the make copy button on the console.

W(code) To store the complete list of line segments created in Phase 1, type "W" followed by the desired code file number. To store the line segments in the third file, for example type "W" followed by "3".

R(code) To recover a list of line segments created at an earlier time, type "R" followed by the desired code file number. For example, to recover the eighth file type "R" followed by "8".

Note: The program uses the ASCII equivalent of the character to calculate the position of the file on the Linc tape. On a $620_8$ block tape the permitted files, in order, are: 1-9, :, ;, <, =, >, ?, @, and A - Q. The program also stores a "password" in the file to prevent garbage from being read into the program.

N - The program has a subroutine to allow the numerical input of line segment end points. To implement this feature, type key "N".

C - The Tektronix screen coordinates are from 0 to 1023 in the x direction and from 0 to 780 in the y direction. Often, the problem to be analyzed can be in field coordinates

which do not fall conveniently in this range. By typing key "C", a scale factor may be input to the program which is then used by the program to divide the input data in such a way that it will fall within the range of the Tektronix screen coordinates. Incidentally, the program treats both the scale factor and the input data as integer numbers, so nothing is to be gained by typing in highly accurate field coordinate data. The "C" key does not affect either the cross-hair cursor input or the digitizer input.

D - The program contains a subroutine to allow input of data by means of a graphic tablet or digitizer. To implement this feature type key "D".

DIGITIZING ROUTINE

The digitizing routine will accept input data from the graphic tablet until the "E" key is typed. At this point the control returns to the main program and the cross-hair cursor is displayed.

NUMERIC INPUT ROUTINE

Upon entrance to the numeric input routine, the computer responds by typing "X1=?" and waiting for input data. After the data input following "Y2=?" several keys are operative.

CR - striking the carriage return key causes the computer to respond "X1=?" etc.

/ - striking the "/" key causes the program to use the last endpoint as the first endpoint of a new line segment. The computer response is thus "X2=?" etc.

L - striking the "L" key causes the computer to redraw all lines. This key is frequently used as every input data pair will leave "X1=?" and "Y1=?" typed on the screen - it soon becomes difficult to follow what is happening on the screen unless "L" is frequently implemented.

E - striking key "E" while in the numeric input routine will cause control to be returned to the main program and the cursor is displayed.

Once the desired number of line segments has been created, the second Overlay of the program may be implemented. To do this, strike key "P" followed by key "2". Two comments are appropriate. First, it is not possible to get to Phase 2 from either the numeric input routine or the digitizer routine. The cross-hair cursor must be displayed before control can be passed to Phase 2. Second, all three input methods work together. Thus, it is possible to create part of the assemblage of line segments in the numeric input routine and finish the creation in the cross-hair cursor input routine.

PHASE 1 SUMMARY

A) Cursor Displayed - Operative Keys

1 Use the cursor position as end no. 1 of a new line

2 Use the cursor position as end no. 2 of new line (display the line)

E Erase the indicated line

H Make a hard copy of display

rubout - Erase all lines

W(code) Write the display onto tape in location code

R(code) Read the display at location code into memory

D Go to digitizing routine

N Go to numeric input

C Change N scale factor

P Then 2 go to P-2

B) Digitizing Routine

Accept line segments from digitizer

E Escape to cursor on

C) Numeric Input Routine

Responds X1=?, etc, after Y2=? several keys are operative:

CR Select a new point

/ Repeat point

L Redraw all lines

E Escape to cursor on

PHASE 2 - OPERATIVE KEYS

E - A single block may be erased in Phase 2. To implement this option, place the cross-hair cursor on the desired block centroid and type key "E".

R - All erased blocks may be restored by typing key "R".

S - A single block may be examined by placing the cross-hair cursor on the desired block centroid and typing key "S". After the single block is displayed, the block may be erased by typing key "E". Striking any other key returns without erasing the block. This feature is most useful to determine which centroid belongs to a given block.

A - Striking key "A" will display all of the blocks.

H - A hard copy of the display may be obtained by striking key "H" or pressing the "make copy" switch on the Tektronix console.

To return to Phase 1, strike key "P" followed by key "1".

To pass control to the third Overlay, Phase 3, type key "P" followed by key "3".

Two comments are in order. First, it is more economical in terms of computer work expended to erase unwanted blocks in Phase 2 than in Phase 3. Second, if the computer determines that no blocks can be created from the line segments passed by Phase 1, control is automatically returned to Phase 1. This means that it is not possible to get to Phase 3 without at least one block on the screen. To access a Phase 3 save file it is necessary to create a single block, and pass it from Phase 1 to Phase 2 and then onto Phase 3.

At that point, the Phase 3 save file may be read.

PHASE 2 SUMMARY

E Erase the block indicated

A Display all blocks

S Display the single block indicated - E Erases the block, any other key returns without erasing block

H Make a hard copy of the display

R Restore all erased blocks

P then 1 go to Phase 1

P then 3 go to Phase 3

PHASE 3 - OPERATIVE KEYS

Iteration Cycle Not Running

G - To begin or continue the iteration cycle type key "G"

D - As the Tektronix is a storage CRT all images drawn on the screen remain on the screen until erased. To redisplay the system of blocks type key "D".

Z - To remove all inertia from the system type key "Z" to set all velocities to zero. This key is useful in the consolidation phase of the program in conjunction with the "V" key as described in a later section.

H - To make a hard copy of the blocks displayed on the screen type key "H" or depress the "make copy" switch on the Tektronix console.

T - To display the surface properly types which have been declared in the cursor routine, type key "T". The program displays a number from 1 to 9 at the midpoint of the edge of the block. Those surfaces having surface type Ø (the default value) are not indicated.

W - To store page zero (a variable list) and all block data, type key "W". The program writes this data on Linc tapes for future retrieval. This feature can be used to store the consolidated block assemblage and identical problems can be run to study the effect of certain parameters. Only one file can be written or read by Phase 3, so no "code" is required.

R - To read a previously stored Phase 3 write file, type "R". The program reads page zero and the block data, essentially

defining a new problem. A problem may be written on tape and returned to at a later time. As noted earlier, it is not possible to gain access to Phase 3 without going through Phase 1 and Phase 2. The best method of access is to create a single block in Phase 1 and pass it on to Phase 3. Upon typing key "R", the stored problem will be recovered. It is important to note that only the default friction value is stored in page zero. Friction properties for surface types 1 - 9 must be re-entered if the problem is changed. Note that it is possible to use the Linc tape utility "KBEX" to go directly to Phase 3, but this requires knowledge of several starting addresses.

V - The contact vectors of each block may be displayed by typing key "V". The stability of a block can be assessed by repeatedly typing key "V" and noting the variation of the position and length of the contact vectors. Note, however, that while the iteration cycle is not running, new contacts are not being detected (subroutine UPDATE) and repeated typing of key "V" may allow blocks to punch through edges. It is recommended that no more than 10 "V" keys by typed without typing key "G".

L - The weights of all blocks, all externally applied loads and joint fluid pressures are displayed when key "L" is depressed.

J - To input joint fluid pressures, type key "J". The program responds by displaying the cross-hair cursor and waiting.

Position the cross-hair cursor on the desired joint segment and type the desired value of pressure followed by a carriage return. The cursor is then re-displayed. Additional pressure data may then be entered by the above procedure. Alternatively, a carriage return exists from the routine. Note that if two line segments are adjacent the logic of the program will apply to fluid pressure to both surfaces.

C - Typing key "C" displays the cross-hair cursor and allows entry to several input routines described in a later section.

I - By typing key "I", four additional input routines may be accessed by typing an additional key. These keys are:

F - If key "F" is typed following key "I", the routine to define surface friction property types is accessed. To define the friction coefficient corresponding to each numbered surface type, place the horizontal cursor on the same line as the desired surface type, type the "." key followed by a 3 digit decimal value of the friction coefficient, and end with a carriage return. After all desired friction coefficients have been defined, another carraige return will give control back to the main routine. Note that the maximum friction coefficient is 0.999 and that the value actually used by the program differs by .001 due to a validity check.

L - Typing key "L" following key "I" accesses the same numerical input routine described under key "0" in the

cursor routine.

O - Typing key "O" following key "I" allows the user to define several options including the options to print values of applied loads and contact vectors, define the vector length scale factor, and automatically make copies and stop the program after a desired interval. The kinetic energy damping routine should be used with extreme caution.

U - If key "U" is typed following key "I", a routine to define user units is entered. At the present time the only result of entering this routing is to cause a set of divided axes, labeled in desired units to be displayed on the screen.

X - By typing key "X" the iteration cycle counter is reset to zero. This routine is useful to set the cycle counter to zero after the consolidation phase so that the problem can begin at zero time.

Q - Typing key "Q" accesses several routines to vary some of the dynamic parameters and block weights. Its primary function is in program development and debugging.

M - Typing key "M" puts the cross-hair cursor on the screen and enables the selection of the block to be used for the displacement control mechanism. Place the cursor on the desired block centroid and hit any key except "E". The program guides the user through the specification of the displacement steps,

frequency and direction. Striking key "E" disables the mechanism if it is already set.

P - Upon completion of the problem, control may be passed to Phase 1 by typing key "P".

Iteration Cycle Running

S - To stop the iteration cycle and prepare for input, modification etc. type key "S".

N - While the iteration cycle is running blocks that are moving are being redrawn as they move. To prevent this type key "N". The computer responds by blanking the Tektronix screen. This action is required if the program is to be left unattended as the Tektronix screen can be permanently damaged if an image is displayed for a time longer than about 15 minutes without being redrawn. This option also makes the program run faster since the computer does not have to service the Tektronix for plotting.

A - Plotting of the blocks as they move can be restored by typing key "A". However, this option does not redraw all of the blocks, it only enables the drawing of blocks as they move. This has the advantage of allowing the user to determine zones of movement within a mass, for example. To redraw all of the blocks, both moving and stable, type key "A" followed by key "D".

Several of the keys which are operative when iteration cycle is stopped are also operative when the iteration cycle is running.

These are:

D - display all blocks

H - make a hard copy

T - display surface types

V - display contact vectors

L - display load vectors

Iteration Cycle not Running, Cross-Hair Cursor Displayed

F - To force the program to hold a block fixed in space, place the cross-hair cursor on the desired block centroid and type key "F".

U - To release the status of a previously fixed block, place the cross-hair cursor on the desired block centroid and type key "U".

E - Blocks can be erased by placing the cross-hair cursor on the desired block centroid and typing key "E". However, as mentioned earlier, it is more economical in terms of computer effort to erase blocks while in Phase 2.

O - Typing key "O" writes the prompt message "Select Single Block". Place the cross-hair cursor on the desired block, hit any key and the program displays just the one block. Also displayed on the screen are the block centroid coordinates and the magnitude of the applied loads. Additionally, if switch zero on the computer console is in the up position, pertinent force and velocity data are displayed. Finally, an opportunity is presented to numerically change the values of

the applied loads. This routine exits the cursor routine automatically.

1 - Applied loads may be input from the cursor routine by placing the cursor on the desired block centroid and typing key "1". The cross-hair cursor is then moved to a position defining the magnitude and direction of the desired load vector and key "2" is typed.

Ø-9 - Surface property type flags are set in the cursor routine by placing the cross-hair cursor on the desired block edge and typing a key from "Ø" to "9". This flag alerts the program to search the friction table for a specific friction value.

Any other key removes the cursor and transfers control back to iteration cycle not running status.

There are two external "flags" available to the user to modify the execution of the program. These are data switches on the console of the computer. If switch 15 is in the up or on position, the printing of the elapsed cycles and default friction coefficient is inhibited. This is of use when it is desired to have copies that are free of text. The other flag is controlled by switch Ø on the console; it serves multiple purposes in guiding program execution. If switch Ø is in the up position, it is not possible to return to Phase 1; this is done to prevent accidental loss of a program. Switch Ø "on" also causes velocity and acceleration data to be printed when a single block is examined, as well as allowing a message to be printed when the displacement control mechanism is operative.

PHASE 3 SUMMARY

Not Running

G Go (start dynamics)

D Redraw all blocks

Z Set all velocities to zero

H Make hard copy

T Display surface types

W Write display on tape

R Read display from tape

V Display contact vectors

L Display loads & pressures

J Accept joint pressures

C Display cursor

I Input actuation

F Friction U Units

L Loads O Options

X Reset cycles

Q Debug routine

M Access displacement control

P Go to Phase 1

Running

S Stop running

N No plot option

A Activate plotting

Also: D, H, T, V, L

Cursor Displayed

F Fix block indicated

U Unfix indicated block

E Erase block indicated

O Display block indicated

1 First end of applied load vector (centroid) followed by a 2

Ø to 9 Define surface type (friction)

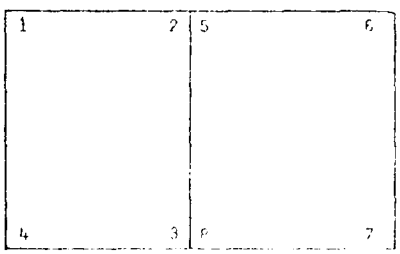
Other keys remove cursor

USEFUL INFORMATION

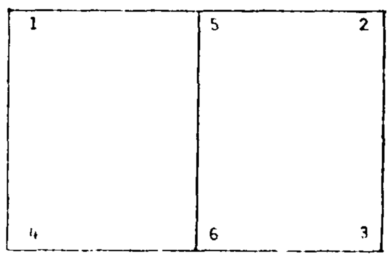
The remainder of this Appendix is devoted to the presentation of information that will be of use to potential users of the program. Some of this information is intended to make it easier for an untrained user to begin working with the program, some of it is intended to aid those interested in program development and some of it is simply odds and ends. No apology is offered for the rather rambling nature of the presentation.

Block creation

In the first overlay or main section of the program, line segments are drawn on the Tektronix screen using the cross-hair cursor, a numerical coordinate input routine or the graphic input tablet. At this stage of the program we are only drawing line segments. Thus it is not necessary to draw each block individually.

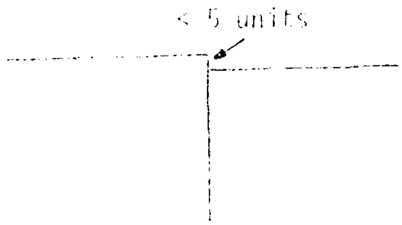



not required




better way

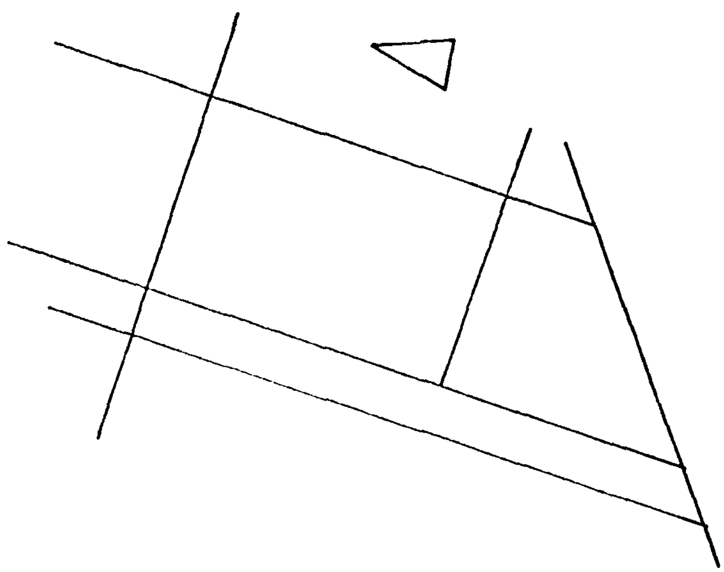
The program detects intersections and overlaps and treats them as such. Incidentally the program has a built in error factor of 5 screen units (out of 1023 x or 768 y). It is therefore impossible to create a situation such as:



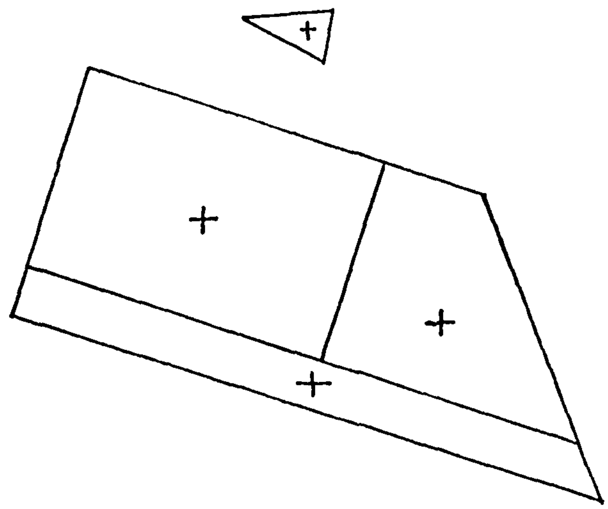

The program will merge

the points into

Always remember that line segments that do not define a closed area will be rejected by the program Overlay 2 (see following paragraph). In the second Overlay of the program, the computer scans all line segments created in the first Overlay to determine which line segments will form closed areas. For example, if the following line segments were created in Phase 1, (or the first Overlay):

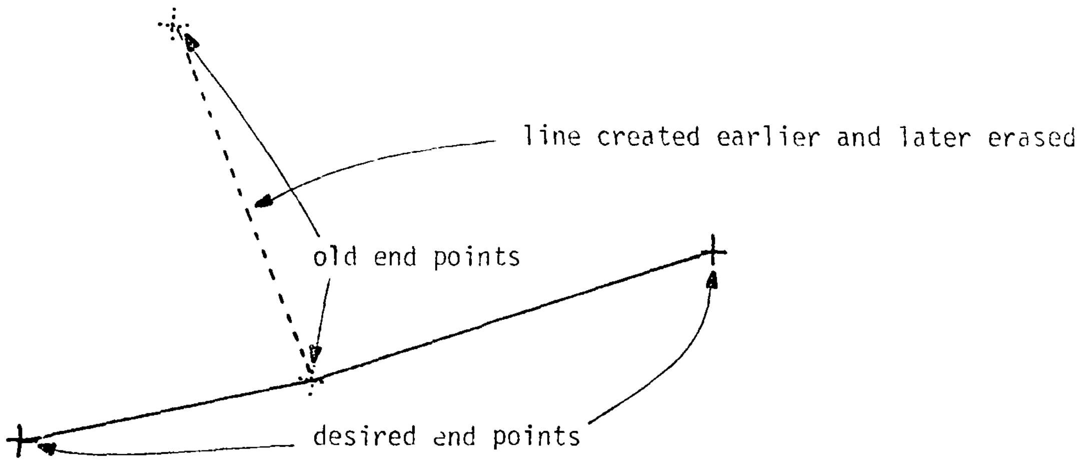


Phase 2 (second Overlay) would return the following blocks:



It must be emphasized that closed areas must be drawn in Phase 1 if blocks are desired in the main part of the program. If a desired line segment has been inadvertently omitted, there is no recourse other than to return to Phase 1 and begin anew.

In Phase 1, use rubout rather than erase if possible as the program remembers all points created since the last rubout command. Thus, if you desired to create a line but had created and erased a previous line, the program would, if it considered the action proper, divert the line to include the previous line's end point.




This happens very easily, be aware of why it happens.

As the Tektronix 4010-1 is a storage oscilloscope and not a television screen, all information drawn on the screen is stored on the screen. Under no circumstances use the page key to clear the display. This leads to a minor state of confusion as to what the program is doing. Especially serious is the situation that occurs if you use the page key when the cross-hair cursor is displayed. The effect of this is to place the screen in ALPHA mode (ASCII input) while the governing software is still in GIN MODE (graphic input). When this occurs, you no longer will be able to communicate with the computer through the Tektronix, and the computer will be hung-up in the graphic input loop. This isn't really as serious as it looks. For some reason, striking the

return key several times will bring the cursor back. However, this is not fool proof - if you strike the return key quickly, it is possible that the program will give the Tektronix the order to take the cursor down before it actually gets it back on the screen. In this case the computer is no longer confused, but quite often the operator is. Enough said, the best solution is to not touch the page key when using this program.

Linc tapes

The Linc tape system is a unique mixture of the operating advantages of a disk system and the lower cost of a magnetic tape format. The addresses of the storage blocks are written on the tape and the software can search the tapes in either direction for a specific block address and, once it is found, read, write or overwrite starting at that address. The present form of the Distinct Element program relies heavily on the Linc tapes and the following paragraphs present information that could be of use to someone using the program.

The system used for this study has two drives - unit 0 and unit 1. Unit 0 is used by the program for the Phase 1 save files. The save file handling routine, subroutine TAPE, does not check the tape file directory before writing nor does it append a title to the directory for the save file. It is thus a good idea to use a blank tape on unit 0 and maintain a separate "directory" of the save files. Unit 1 is used for a tape that has the three overlays and the introduction to the program written on it. (Incidentally the

[illegible] is accessed by placing a "blank" tape on unit 0, a "program" [illegible] unit 1 and typing "HELP". The program takes it from there!) [illegible] on unit 1 is also used to store the Phase 3 save file. It is important to note that the file directories do not "know" about the overlays and save file and thus it is up to the user to protect all file space from block $150_8$ onward.

[illegible] Linc tape furnished software used in this study did not [illegible] a sophisticated operating system. The fact that not having [illegible] sophisticated operating system led to additional memory (= larger [illegible]) was offset by the fact that the overlays must be "done by [illegible]".

[illegible] Linc tape utilities have the capability to move data from [illegible] memory and vice versa. The overlays of the program are [illegible] images of memory written onto tape. For the present study [illegible] addresses on the tape on unit 1 are:

| tape file | beginning block number * | number of blocks |
|---|---|---|
| Phase 1 | $350_8$ | $55_8$ |
| Phase 2 | $450_8$ | $37_8$ |
| Phase 3 | $510_8$ | $37_8$ |
| P-3 save file | $150_8$ | up to $200_8$ |
| digital plot routine | $555_8$ | 1 |

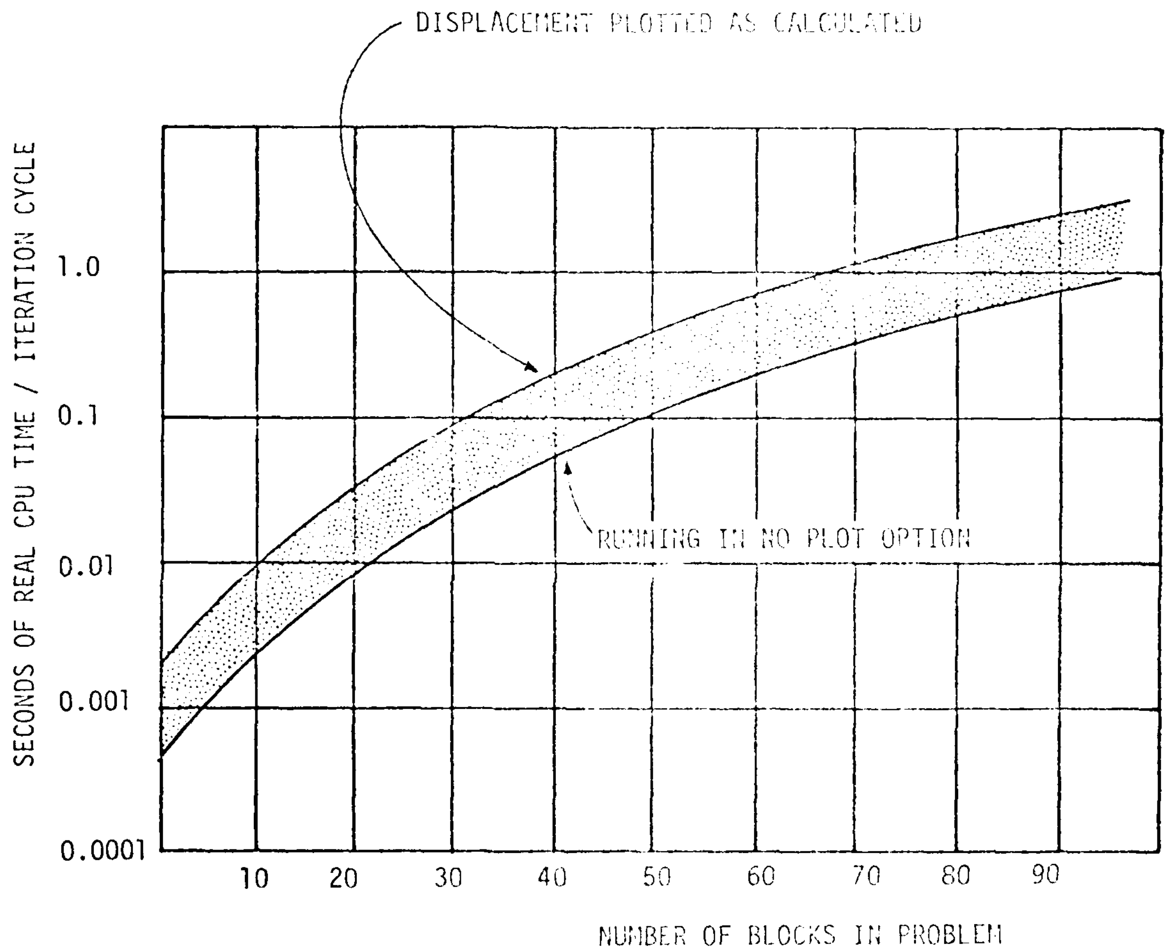
* The Linc tapes used have $620_8$ blocks of $400_8$ words

It is important to point out that the Linc tape routine KBEX, which is used to write the overlays onto tape, does not check the file directory. It is a very easy matter to destroy files on the tape if KBEX is not used with extreme caution.

Execution times

The amount of real time required for execution of a single cycle of the Phase 3 iteration loop is primarily a function of the number of blocks comprising the model in question. The program execution times are also greatly influenced by any program options in use and the amount of "connect" time devoted to machine/user dialog. The option which consumes the most time is, of course, the plotting of the blocks as movement occurs. This is due to the fact that communication across a teletype line occurs under conditions of "programmed I/O" - the CPU must wait between each transfer until the Tektronix is ready to accept more data.

The accompanying graph presents an approximate portrayal of the real time required for the Nova 1220 to perform one complete cycle of the iteration loop as a function of the number of blocks modeled in the program. The graph indicates a range of time required for calculation; the lower end of the range is a fairly accurate representation of the fastest possible calculation times for a given number of blocks. This time can only be realized by running in the "no plot" option. The upper end of the range represents the time required for one cycle of the iteration loop with the plotting option


DISPLACEMENT PLOTTED AS CALCULATED
RUNNING IN NO PLOT OPTION
SECONDS OF REAL CPU TIME / ITERATION CYCLE
1.0
0.1
0.01
0.001
0.0001
10
20
30
40
50
60
70
80
90
NUMBER OF BLOCKS IN PROBLEM

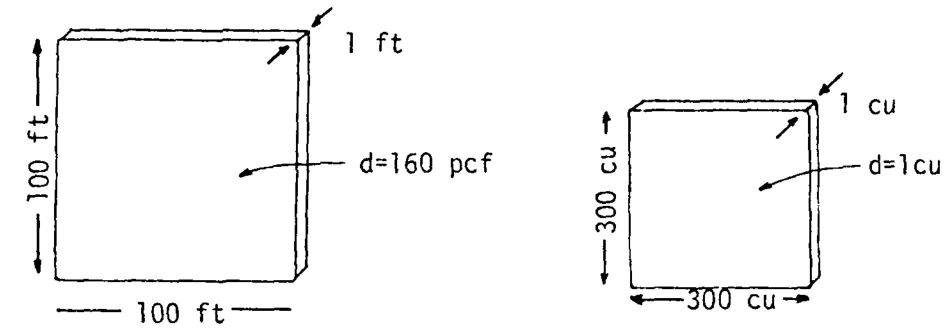
activated and most of the blocks in the program moving. This probably represents an accurate upper limit to the calculation time and the time required for most problems would be somewhat less than that illustrated.

The time dedicated to user/machine dialog is not included in the graph but can be a significant portion of the total time required for program execution. This is especially so for users who are unfamiliar with the program, but increased exposure to the program usually leads to familiarity and an attendant drop in the amount of time required for interaction.

Conversion factors

All calculations performed by the Distinct Element program described in this Appendix utilize variables whose magnitudes and dimensions have been adjusted to give optimum calculation speeds. This has been done in order that double precision variables are avoided and so that all arithmetic is done on integers (integer arithmetic is many times faster than floating point arithmetic in the absence of a floating point processor). In order that someone who wishes to do so may convert to either metric or english units, three conversion factors are presented in the following paragraphs.

The first conversion factor is a defined relationship between physical problem length and that used in the computer program. Consider the following physical situation: a block 100 ft on a side, 1 ft thick, with a unit weight of 160 pcf.




The computer model is drawn in such a way that the equivalent edge lengths are 300 cu (computer units). The unit weight in the computer model is 1 cu (this can be changed by typing "Q" followed by key "W" - the following must be modified if the unit weight is changed). By selecting 300 cu to represent 100 ft, the first conversion factor $f_d$ is automatically defined.

| To get feet or meters multiply the program distance by $f_d$ |
|---|

In this particular example,

$$300 \text{ cu} * f_d = 100 \text{ ft} \quad \text{or}$$

$$f_d = 0.333 \text{ ft/cu}$$

The second conversion factor is a derived relationship between physical problem forces and those used internally in the computer program returning to the example, the real weight of the block is

seen to be:

$$100 \text{ ft} * 100 \text{ ft} * 1 \text{ ft} * 160 \text{ pcf} = 1.6 \times 10^6 \text{ lbs}$$

The weight of the block in computer units is given by the Distinct Element program - in this case it is seen to be 720 cu. The number 720 represents a normalized weight obtained by determining the volume of the block and dividing by 125. The number 125 is related to the tolerance to which points and lines are subjected in Phase 1 and Phase 2. The smallest block allowed is defined to be 5 times the area defined by the screen accuracy (5 x 5). The smallest block area possible is then 125 units; when normalized the smallest block weight allowable is thus 1 cu since the unit weight used in the program is 1 cu. The weight used in the computer program for this example is thus

$$\frac{1}{125} * \frac{100 \text{ ft}}{f_d} * \frac{100 \text{ ft}}{f_d} * \frac{160}{d} \text{ pcf} = W \text{ cu/unit depth}$$

Since $\quad W \text{ real/unit depth} = 100 \text{ ft} * 100 \text{ ft} * 160 \text{ pcf}$

$$W \text{ real} = 125 * f_d^2 * d * W \text{ cu}$$

The conversion factor between real situation force and that used internally by the computer is $f_\ell$

$$f_\ell = 125 * f_d^2 * d$$

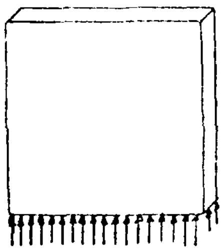
$$\boxed{\text{To get force in pounds or newtons multiply the displayed force by } f_\ell .}$$

In this particular example

$$f = 125 \times 0.333 \times 160 \quad \text{or}$$

$$f = 2222.22 \text{ lb/cu}$$

The third conversion factor relates pressure in physical units such as psf or $N/m^2$ to the units used internally in the computer program. If the base pressure of the real block considered in this example is calculated the quotient of the block weight and the contact area are found.



$$P_{real} = \frac{W}{A} = \frac{100 \text{ ft} \times 100 \text{ ft} \times 1 \text{ ft} \times 160 \text{ pcf}}{100 \text{ ft} \times 1 \text{ ft}}$$

In the computer situation this reduces to

$$P\ (cu) = \frac{\frac{100 \text{ ft}}{f_d} \times \frac{100 \text{ ft}}{f_d} \times \frac{160 \text{ pcf}}{d} \times \frac{1 \text{ ft}}{f_d}}{\frac{100 \text{ ft}}{f_d} \times \frac{1 \text{ ft}}{f_d}}$$

or

$$P_{real} = P\ cu \times fp$$

where $f_p = f_d \cdot d$

| |
|---|
| To get pressure in psf or pascals, multiply the displayed pressure by $f_p$ |

In the example considered, if it were desired to input a joint water pressure whose resultant would balance the weight of the block, its magnitude would be found in the following manner

- real pressure $P = 1.6 * 10^6$ lb/100 ft$^2$ = 16000 psf
- $f_p = f_d * d = 0.333 * 160 - 53.3$ psf/cu
- pressure in computer units = $\frac{P_{real}}{f_p} = \frac{16000}{53.3} = 300$ cu

Equilibrium conditions

The problem of recognition of equilibrium conditions is of paramount importance in the Distinct Element method, as in other explicit finite difference programs. An explicit formulation does not have a "solution" in the sense that an implicit formulation such as a Finite Element analysis does. In the implicit formulation the behavior of each point is related to the other points through a system of equations that can be solved for a given input resulting in a solution. In an explicit formulation, on the other hand, the points communicate only with their nearest neighbors; the "solution" in this case does not necessarily need to be a situation of stable equilibrium. The only way that an equilibrium situation can be recognized is by observing the behavior of the blocks.

The obvious solution to this problem is to observe the blocks flashing on the screen - the movement of the blocks is obvious and it can immediately be recognized if the problem under consideration is unstable. However, the fact that the blocks are not flashing

on the screen does not necessarily indicate that an equilibrium situation has been reached. In the example considered in the previous section, one screen unit of displacement corresponded to four inches of real displacement. In a large problem where the blocks are somewhat confined, thousands of iteration cycles will be needed to get this much displacement; for a program involving 75 blocks the real time for this many calculations could take an hour. This is obviously not a very satisfactory method to determine if equilibrium exists.

The software necessary for more subtle solutions has been incorporated within the present version of the program. At any time during the running of a problem, the program may be stopped (key "S") and any block examined for pertinent data. By displaying the cursor (key "C") then typing key "O" will result in the message "SELECT ANY BLOCK" being displayed on the screen. By placing the cursor on the desired block centroid and striking any key a display of block data will be presented. This data includes: block centroid coordinates (four places to right of decimal point displayed); the unbalanced force sums acting on the block; the block velocities and angle of rotation; and, the values of user applied loads. By examining certain "key" blocks as the program runs it is a relatively simple matter to determine if an equilibrium state has been reached.

Block consolidation

The block data passed onto Phase 3 from the first two overlays contains information pertaining to individual blocks only. The

contact lists do not exist before the start of the program, so the blocks do not know that they have neighbors. When gravity is suddenly switched on, all of the blocks begin to move at once and as block interactions occur, the contact lists are developed. The way in which the block configuration is allowed to interact has a significant effect on the outcome of the program in those instances where a proper mass consolidation is not achieved. An improperly consolidated system of blocks can lead to a diverging solution; this can be recognized by the presence of wildly fluctuating contact forces that bear no relation to the block weights involved.

The blocks should be allowed to consolidate in an initial equilibrium position before the actual problem is run. This can usually be accomplished by the judicious placement of restraining blocks; these are subsequently removed to begin the actual problem. To actually consolidate the mass a good deal of time must be spent observing the behavior of the blocks and intervening to guide the program. Just switching gravity on without regard to consolidation of the blocks can easily lead to situations where pressure waves travel through the mass and prevent the blocks from reaching an equilibrium state.

Several bits of information are related in the following sentences that should be helpful to potential users of the program. First of all it is very helpful to start the problem with all frictional properties set to zero (the program automatically does this unless the user changes the friction table). The first block interactions often involve high contact forces; if the friction

coefficients of the surfaces are other than zero, situations can arise whereby relatively large forces are "locked-in" only to be released when just the right contact occurs. By starting with a zero value of the friction coefficient, shear resistances do not develop along the joints and in conjunction with the velocity zeroing technique described below, the restrained system of blocks comes to equilibrium. At this point, the restraining blocks can be removed and the program allowed to run.

The technique of properly consolidating a system of blocks involves zeroing the block velocities at the correct time; the system of blocks cannot reach equilibrium unless all inertial effects are removed. It is possible to gain insight into the status of a block mass by examining the behavior of the contact vectors. The key "V" is used to display the contact forces whenever it is struck; this is accomplished by setting a plot flag, going once through the iteration cycle and then taking the flag down. This is especially useful if the program is in the stopped mode since the "V" key can be used to step through the iteration cycle incrementally. The variation in the length and angle of the contact vectors is indicative of the relative stability of the behavior. Well consolidated systems of blocks display little variation in length or inclination of the contact vectors. To achieve this state the user must examine the behavior of the system and zero the block velocities (key "Z") when the system is in an "average" state. An "average" state is exactly what it sounds like - the length of the contact vectors are approximately the

average of the variation in length, and the inclination of the contact vectors is approximately midway between the extreme inclinations. This can rarely be achieved in one attempt, and the amount of time required to do it successfully increases with the degree of confinement of the problem (i.e., tunnel models are much more difficult to consolidate than slope models).

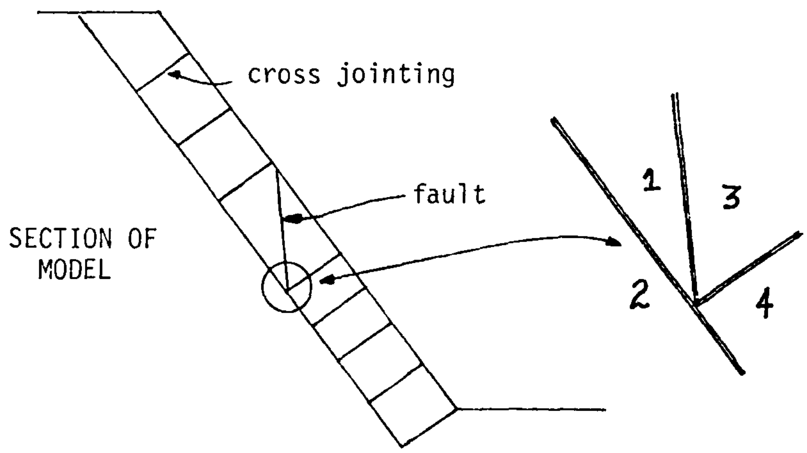
A few words of caution are in order. Stepping through the iteration cycle using key "V" neglects the very important subroutine calls to UPDAT. Unless UPDAT is called, new contact points are not detected nor are contact data updated. The result of this is that blocks can move through one another. As a rule of thumb, no more than about 25 consecutive cycles should be run by using the "V" key without using the "G" key which does call UPDAT. Potential users will find that applying loads incrementally rather than all at once will result in well behaved models. The same is true for friction coefficients; gradually increasing the friction coefficient to the required value also results in well behaved models.

Special problems

Two specific problem geometries that can lead to obviously improper solutions have been identified during the course of this research. Both involve shortcomings in the contact determining logic; the problems are identical in nature but whereas one is easily overcome, the other requires that some care be expended in block consolidation to prevent its occurance. The problems will be illustrated by reference to the specific geometries in which they

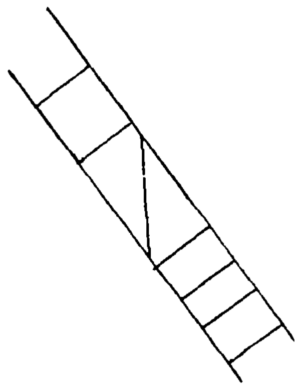
were first identified.

The first of the two problems occurred during the analysis of a rock slope which had failed. (This incidentally, was a real problem - the analysis was performed in collaboration with Dr. Michael Bukovansky of the consulting firm of Dames & Moore.) The geometry of the problem:

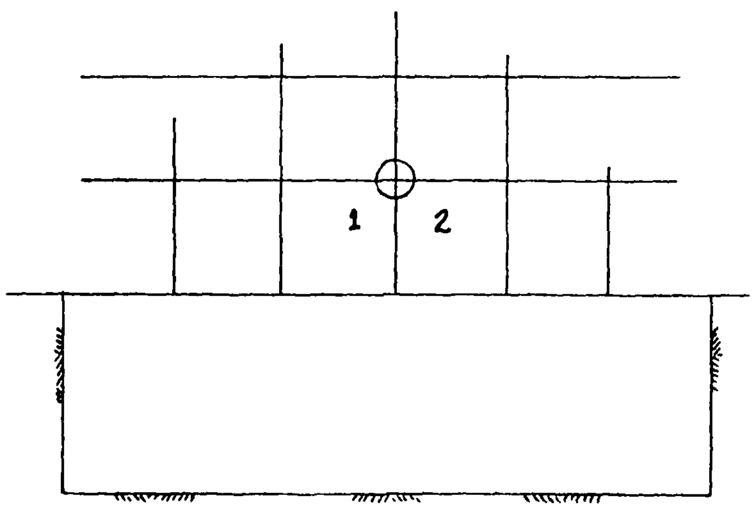



The area under consideration is shown highly magnified: four separate blocks are identified. Geological investigation indicated the presence of a fault plane that could lead to the development of a "chiseling" action - the upper blocks could slide down and "pry" the lower blocks. The initial analyses performed using the Distinct Element program failed to reproduce the expected failure. Close examination of the behavior indicated that instead of sliding past block #3, the lower point of block #1 was contacting block #4 and "hanging up"; the net result being that the entire assemblage of

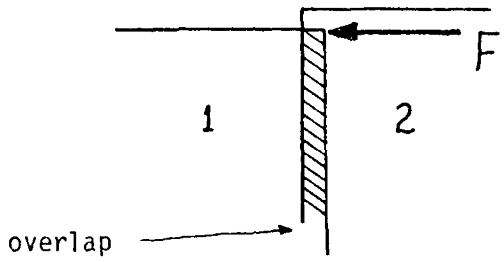
blocks stabilized. In the real situation, any such contact would result in fracture development at the point - in the Distinct Element program such cracking is presently not modeled. This problem was solved simply by moving the position of the cross joint between block #3 and block #4 to a slightly lower position on the slope as illustrated below.



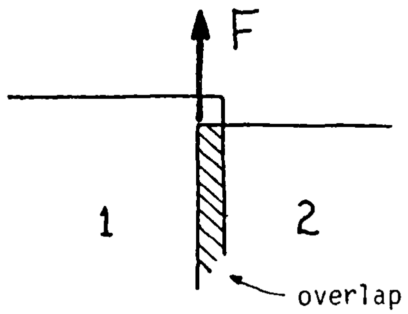
The second problem is of a similar nature; its occurance is rare and is usually due to improper block consolidation. The problem was identified in a model similar to that illustrated and resulted in the stability of a model which should have failed.



To illustrate the problem a magnified section of the model is required; a contact between blocks #1 and #2, circled in the sketch, is illustrated




The overlap of the two blocks results in a contact force F tending to push the blocks apart. However, in an improperly consolidated block mass, especially one with high horizontal forces applied before the mass is allowed to move, the contact situation could look like this after the first iteration.




Depending upon which "contact" is first discovered by the contact seeking logic edge #1 of block #1 could be identified as the edge in contact. The resultant force would thus act to prevent the downward movement of block #2. This problem has not arisen in models where proper consolidation steps have been taken. As

insurance, however, all models tested where this problem could occur have been allowed to fail as part of the analyses, to make certain that the problem was not occurring.

For those geometries to be tested where the occurance of this problem is a possibility, special care can be taken during the consolidation phase to prevent its occurance. This often involves consolidation of segments of the model on an individual basis and then pushing the individual segments together to form the model.

# APPENDIX C

## LISTING OF THE DISTINCT ELEMENT PROGRAM

This Appendix contains listings of all of the subroutines necessary to build the three overlays of the Distinct Element program used in this dissertation. Most of the Phase 1 and Phase 2 routines are written in Fortran; a few are written in Data General Nova assembly language. All of the Phase 3 subroutines are written in Nova assembly language.

At first glance, the assembly language subroutines may appear to be of little value to those unfamiliar with Data General computers; this is, however, not the case. Assembly language programming differs very little from the techniques used in programable calculators and in fact rarely involves anything more sophisticated than moving data between memory and accumulators, performing arithmetic functions, and occasionally jumping to a subroutine. The listings presented are interspersed with numerous comments and the straightforward logic of the program makes them very readable.

As an aid to potential users a list of the subroutines loaded in each overlay is presented next.

Note

The order in which the subroutines are loaded is immaterial unless the digital plotting routine (subroutine PLOT, Cundall, 1974) is desired. In this case, the plotting routine is read from the

tape, in absolute binary, whenever it is needed. The routine starts at location $440_8$ and thus overwrites the first subroutine in memory. If the loading sequence places TRANS at the start of memory, the overwriting will not disrupt the program.

Preceeding the listing of the Phase 3 subroutines is a list of the Phase 3 global symbols. These are primarily entry point addresses and frequently used variables. The listing begins on Page C-37.

```
C---MAIN PROGRAM (OVERLAY NUMBER ONE)------
           COMMON I1(768),I2(768),LIST(32),
      *     LISTC(128),IX(512),IY(512)
           COMMON/HANDY/N,L,IACC
   75      N=0
           L=0
           IACC=5
           IFACT=1
  1        MJX=JX2
           MJY=JY2
           LCODE=0
           KODE=0
           CALL CURS(I,JX1,JY1)
           CALL CHARO(159)
           IF(N.EQ.0 .OR. I.NE.178) GO TO 80
           LCODE=1
           JX2=JX1
           JY2=JY1
           JX1=MJX
           JY1=MJY
           GO TO 103
  80       IF(I.NE.196) GO TO 400   ;"D" FOR DIGITIZER
           KODE=1
           GO TO 100
 400       IF(I.EQ.195) GO TO 210   ;"C" TO CHANGE FACTOR
           IF(I.NE.206) GO TO 104   ;N FOR NUM. INPUT
           KODE=-1
           GO TO 201
  104      IF(I.EQ.200) GO TO 72    ;"H" FOR HARD COPY
           IF(I.EQ.197) GOTO 73     ;"E" FOR ERASE
           IF(I.EQ.208) GOTO 76     ;"P" FOR "PHASE..."
           IF(I.EQ.255)GOTO 74      ; RUBOUT ALL LINES
           IF(I.EQ.215) GO TO 81    ;"W" FOR WRITE
           IF(I.NE.210) GO TO 87    ;MUST BE "R" TO READ
           CALL CHARI(I)
           NFIRST=(I-177)*12        ;GET FILE CODE
           CALL CHARO(155)
           CALL CHARO(140)
   83      CALL TAPE(1,NFIRST,I1,I1,NERR)
           IF(NERR.EQ.0) GO TO 82
           PAUSE TAPE ERROR---HIT ANY KEY TO REPEAT
           GO TO 83
   82      N=LIST(1)
           L=LIST(2)
           IF(LIST(3).NE.13286) GO TO 75
           DO 84 LX=1,L
           IA=I1(LX)
           IB=I2(LX)
           CALL PLOTS(0,IX(IA),IY(IA))
   84      CALL PLOTS(1,IX(IB),IY(IB))
           CALL CHARO(159)
           GO TO 1
  81       CALL CHARI(I)
           NFIRST=(I-177)*12
           LIST(1)=N
```

```
      LIST(2)=L
      LIST(3)=13286
 86   CALL TAPE(2,NFIRST,I1,I1,NERR)
      IF(NERR.EQ.0) GO TO 1
      PAUSE TAPE ERROR---WRITE PROTECT ON ? HIT A KEY
      GO TO 86
 87   IF(I.NE.177) GOTO 1      ;"1" FOR FIRST END OF LINE
      IF(KODE.EQ.0) GO TO 103
100   CALL DIGIT(JX1,JY1,ICODE)
      IF(ICODE.NE.0) GO TO 1
      GO TO 103
201   ACCEPT"   X1=",JX1," Y1= ",JY1
      JX1=JX1/IFACT
      JY1=JY1/IFACT
103   IF(N.EQ.0) GO TO 4
      DO 2 NN=1,N
      IF(IABS(IX(NN)-JX1).GT.IACC) GOTO 2
      IF(IABS(IY(NN)-JY1).GT.IACC) GOTO 2
      IFIRST=NN
      GOTO 3
  2   CONTINUE
      GOTO 4
  3   JX1=IX(IFIRST)
      JY1=IY(IFIRST)
      IF(LCODE .EQ. 1) GO TO 108
      CALL CHARO(135)
      IF(KODE)202,14,109
  4   IF(L.EQ.0) GOTO 12
      CALL LINEX(JX1,JY1,IXR,IYR,NHIT,LL)
      IF(NHIT.EQ.1) GO TO 8
 12   IFIRST=N+1
      GOTO 13
  8   JY1=IYR
      JX1=IXR
      IFIRST=N+1
      L=L+1
      I1(L)=IFIRST
      I2(L)=I2(LL)
      I2(LL)=IFIRST
      CALL CHARO(135)
 13   IX(IFIRST)=JX1
      IY(IFIRST)=JY1
      CALL CROSS(JX1,JY1)
      N=IFIRST
      IF(LCODE .EQ. 1) GO TO 108
      IF (KODE) 202,14,109
202   ACCEPT"  X2=",JX2," Y2=",JY2
      JX2=JX2/IFACT
      JY2=JY2/IFACT
      GO TO 108
109   CALL DIGIT(JX2,JY2,ICODE)
      GO TO 108
 14   CALL CURS(I,JX2,JY2)    ;GET POINT 2
      CALL CHARO(159)
      IF(I.NE.178) GOTO 14
```

```
108   IF(IABS(JX2-JX1).GT.IACC) GOTO 15
      IF(IABS(JY2-JY1).GT.IACC) GOTO 15
      IF(KODE)202,14,109
15    IF(N.LE.1) GOTO 25
      DO 16 NN=1,N
      IF(NN.EQ.IFIRST) GOTO 16
      IF(IABS(IX(NN)-JX2).GT.IACC) GOTO 16
      IF(IABS(IY(NN)-JY2).GT.IACC) GOTO 16
      ISEC=NN
      GOTO 17
16    CONTINUE
      GOTO 18
17    JX2=IX(ISEC)
      JY2=IY(ISEC)
      CALL CHARO(135)
      GOTO 28
18    IF(L.EQ.0) GOTO 25
      CALL LINEX(JX2,JY2,IXS,IYS,NHIT,LL)
      IF(NHIT.EQ.1) GO TO 26
25    ISEC=N+1
      GOTO 27
26    JX2=IXS
      JY2=IYS
      ISEC=N+1
      L=L+1
      I1(L)=ISEC
      I2(L)=I2(LL)
      I2(LL)=ISEC
      CALL CHARO(135)
27    IX(ISEC)=JX2
      IY(ISEC)=JY2
      CALL CROSS(JX2,JY2)
      N=ISEC
28    JXD=JX2-JX1
      JYD=JY2-JY1
      IF(IABS(JYD).GT.IABS(JXD)) GOTO 60
      ISWY=0
      IF(JX2.GT.JX1) GOTO 29
      GOTO 49
60    ISWY=1
      IF(JY2.GT.JY1) GOTO 29
49    JXL=JX2
      JXR=JX1
      JYL=JY2
      JYR=JY1
      IPL=ISEC
      IPR=IFIRST
      GOTO 30
29    JXL=JX1
      JXR=JX2
      JYL=JY1
      JYR=JY2
      IPL=IFIRST
      IPR=ISEC
30    IF(ISWY.EQ.0)GOTO 61
```

```
      H=FLOAT(JXR-JXL)/FLOAT(JYR-JYL)
      NXTOT=0
      DO 62 NY=1,N
      IF(IY(NY).GT.JYR.OR.IY(NY).LT.JYL)GO TO 62
      IF(NY.EQ.IPL.OR.NY.EQ.IPR) GOTO 62
      IXX=IFIX(H*FLOAT(IY(NY)-JYL))+JXL
      IF(IABS(IXX-IX(NY)).GT.IACC) GOTO 62
      NXTOT=NXTOT+1
      LIST(NXTOT)=NY
   62 CONTINUE
      GOTO 63
   61 H=FLOAT(JYR-JYL)/FLOAT(JXR-JXL)
      NXTOT=0
      DO 31 NX=1,N
      IF(IX(NX).GT.JXR.OR.IX(NX).LT.JXL) GOTO 31
      IF(NX.EQ.IPL.OR.NX.EQ.IPR) GOTO 31
      IYY=IFIX(H*FLOAT(IX(NX)-JXL))+JYL
      IF(IABS(IYY-IY(NX)).GT.IACC) GOTO 31
      NXTOT=NXTOT+1
      LIST(NXTOT)=NX
   31 CONTINUE
   63 KOUNT=0
C
      IF(NXTOT-1)50,53,33
   33 IND=0
C--ORDER POINT LIST IN INCREASING X (OR Y)--
      DO 32 NXX=2,NXTOT
      NX1=LIST(NXX-1)
      NX2=LIST(NXX)
      IF(ISWY.EQ.1) GOTO 47
      IF(IX(NX2).GE.IX(NX1)) GOTO 32
      GOTO 48
   47 IF(IY(NX2).GE.IY(NX1)) GOTO 32
   48 LIST(NXX-1)=NX2
      LIST(NXX)=NX1
      IND=1
   32 CONTINUE
      IF(IND.EQ.1) GOTO 33
   53 IL=IPL
      IR=LIST(1)
      GOTO 51
   50 IL=IPL
      IR=IPR
   51 KOUNT=KOUNT+1
      NINT=0
      LOLD=L
      DO 35 LK=1,LOLD
C--BEGIN LINE SEARCH FOR THIS SEGMENT--
      IF1=I1(LK)
      IF2=I2(LK)
      IF(IF1.EQ.IL.AND.IF2.EQ.IR) GOTO 34
      IF(IF1.EQ.IR.AND.IF2.EQ.IL) GOTO 34
      IF(IF1.EQ.IL.OR.IF1.EQ.IR.OR.IF2.EQ.IL.OR.IF2.EQ.IR)GOTO 35
      CALL OVLAP(IX(IL),IX(IR),IX(IF1),IX(IF2),IX5,IX6,NS1)
      IF(NS1.EQ.0) GOTO 35
```

```
      CALL OVLAP(IY(IL),IY(IR),IY(IF1),IY(IF2),IY5,IY6,NS2)
      IF(NS2.EQ.0) GOTO 35
      CALL INSEC(IX(IL),IX(IR),IY(IL),IY(IR),IX(IF1),IX(IF2),
     *      IY(IF1),IY(IF2),IX5,IX6,IY5,IY6,INX,INY,NS3)
      IF(NS3.EQ.0) GOTO 35
C--A CROSSING HAS BEEN FOUND--
      N=N+1
      IX(N)=INX
      IY(N)=INY
C--CREATE NEW LINE--
      L=L+1
      I2(LK)=N
      I1(L)=N
      I2(L)=IF2
C--TOTAL CROSSING POINTS INCREMENTED--
      NINT=NINT+1
      LISTC(NINT)=N
   35 CONTINUE
      IF(NINT-1) 41,38,37
   37 NIT=0
      DO 36 NN=2,NINT
      L1=LISTC(NN-1)
      L2=LISTC(NN)
      IF(ISWY.EQ.1) GOTO 46
      IF(IX(L2).GE.IX(L1)) GOTO 36
      GOTO 45
   46 IF(IY(L2).GE.IY(L1)) GOTO 36
   45 LISTC(NN-1)=L2
      LISTC(NN)=L1
      NIT=1
   36 CONTINUE
      IF(NIT.EQ.1) GOTO 37
   38 ILEFT=IL
      NUT=1
   39 L=L+1
      I1(L)=ILEFT
      I2(L)=LISTC(NUT)
      CALL PLOTS(0,IX(ILEFT),IY(ILEFT))
      CALL PLOTS(1,IX(I2(L)),IY(I2(L)))
      CALL CROSS(IX(I2(L)),IY(I2(L)))
      ILEFT=LISTC(NUT)
      IF(NUT.GE.NINT) GOTO 40
      NUT=NUT+1
      GOTO 39
C--LAST LINE FOR THIS SEGMENT
   40 L=L+1
      I1(L)=ILEFT
      I2(L)=IR
      CALL PLOTS(0,IX(ILEFT),IY(ILEFT))
      CALL PLOTS(1,IX(IR),IY(IR))
      GOTO 34
C--NO CROSSINGS ON THIS SEGMENT (JUST ONE LINE TO CREATE)--
   41 L=L+1
      I1(L)=IL
      I2(L)=IR
```

```
         CALL PLOTS(0,IX(IL),IY(IL))
         CALL PLOTS(1,IX(IR),IY(IR))
   34    IF(KOUNT-NXTOT) 56,52,54
   56    IL=LIST(KOUNT)
         IR=LIST(KOUNT+1)
         GOTO 51
   52    IL=LIST(KOUNT)
         IR=IPR
         GOTO 51
   54    IF(KODE)203,1,100
  203    CALL CHARO (159)
         CALL CHARI(MCODE)
         IF(MCODE.EQ.197) GO TO 1         ;"E" TO ESCAPE NUM. INPUT
         IF (MCODE.EQ.141) GO TO 201    ; "CR" FOR NEW X1,Y1
         IF(MCODE.NE. 204) GO TO 301     ;"L" TO REDRAW LINES
         CALL CHARO(155)
         CALL CHARO(140)
         DO 302 NL=1,L    ;REPLOT ARRAY OF LINES
         IAA=I1(NL)
         IBB=I2(NL)
         CALL PLOTS(0,IX(IAA),IY(IAA))
  302    CALL PLOTS(1,IX(IBB),IY(IBB))
         CALL CHARO(159)
         GO TO 203
  301    IF(MCODE.NE.175) GO TO 205   ;"/" TO REPEAT POINT
         JX1=JX2
         JY1=JY2
         GO TO 103
  205    TYPE"  ?"
         GO TO 203
   72    CALL HARD
         GO TO 1
   73    CALL ERASE(JX1,JY1)
         GOTO 1
   74    CALL CHARO(155)
         CALL CHARO(140)
         GO TO 75
   76    CALL CHARI(IN)
         IF(IN.NE.178) GOTO 1
         CALL CHARO(155)
         CALL CHARO(140)
         LIST(1)=N
         LIST(2)=L
         LIST(3)=IACC
         CALL OVLAY(2,I1)
         GO TO 1
  210    ACCEPT "  NEW SCALE FACTOR ?  " , IFACT
         GO TO 1
         END ; THANK GOODNESS!!!
```

```
      SUBROUTINE LINEX(IXH,IYH,IXR,IYR,NHIT,LINE)
C--ROUTINE TO DETECT IF LINE IS NEAR POINT--
      COMMON I1(768),I2(768),LIST(32),
     * LISTC(128),IX(512),IY(512)
      COMMON/HANDY/N,L,IACC
      DO 5 LL=1,L
      IP1=I1(LL)
      IP2=I2(LL)
      IX1=IX(IP1)
      IY1=IY(IP1)
      IX2=IX(IP2)
      IY2=IY(IP2)
      IYD=IY2-IY1
      IXD=IX2-IX1
      IF(IABS(IYD).GT.IABS(IXD)) GOTO 6
      IF(IX2.GT.IX1) GOTO 7
      IF(IXH.LT.IX2.OR.IXH.GT.IX1) GOTO 5
    9 H=FLOAT(IYD)/FLOAT(IXD)
      IYG=IFIX(H*FLOAT(IXH-IX1)+0.5)+IY1
      IF(IABS(IYG-IYH).GT.IACC) GOTO 5
      IYR=IYG
      IXR=IXH
      GOTO 8
    7 IF(IXH.LT.IX1.OR.IXH.GT.IX2) GOTO 5
      GOTO 9
    6 IF(IY2.GT.IY1) GOTO 10
      IF(IYH.LT.IY2.OR.IYH.GT.IY1) GOTO 5
   11 H=FLOAT(IXD)/FLOAT(IYD)
      IXG=IFIX(H*FLOAT(IYH-IY1)+0.5)+IX1
      IF(IABS(IXG-IXH).GT.IACC) GOTO 5
      IXR=IXG
      IYR=IYH
      GOTO 8
   10 IF(IYH.LT.IY1.OR.IYH.GT.IY2) GOTO 5
      GOTO 11
    5 CONTINUE
      NHIT=0
      RETURN
    8 NHIT=1
      LINE=LL
      RETURN
      END
```

```
      SUBROUTINE ERASE(IXH,IYH)
C--TO ERASE ONE LINE & RE-DRAW SYSTEM--
      COMMON I1(768),I2(768),LIST(32),
     * LISTC(128),IX(512),IY(512)
      COMMON/HANDY/N,L,IACC
      CALL LINEX(IXH,IYH,IXR,IYR,NHIT,LINE)
      IF(NHIT.EQ.0) RETURN
C--ERASE SCREEN--
      CALL CHARO(155)
      CALL CHARO(140)
C--CUT OUT LL; SHUFFLE DOWN REST--
      LL=LINE
      IF(LL.EQ.L) GOTO 2
      L1=L-1
      DO 1 LK=LL,L1
      I1(LK)=I1(LK+1)
    1 I2(LK)=I2(LK+1)
    2 L=L-1
      DO 3 LX=1,L
      IA=I1(LX)
      IB=I2(LX)
      CALL PLOTS(0,IX(IA),IY(IA))
    3 CALL PLOTS(1,IX(IB),IY(IB))
      CALL CHARO(159)
      RETURN
      END
```

```
      SUBROUTINE INSEC(IX1,IX2,IY1,IY2,IX3,IX4,IY3,IY4,
     *      IX5,IX6,IY5,IY6,IX,IY,NSUC)
      ID1=IX2-IX1
      ID2=IY2-IY1
      ID3=IX4-IX3
      ID4=IY4-IY3
      IF(ID1.EQ.0) GO TO 1
      IF(ID2.EQ.0) GO TO 2
      IF(IABS(ID2).EQ.IABS(ID1)) GO TO 3
      IF(IABS(ID1).GT.IABS(ID2)) GO TO 4
   10 IF(IABS(ID3).GT.IABS(ID4)) GO TO 14
      H1=FLOAT(ID1)/FLOAT(ID2)
      IX1L=IFIX(H1*FLOAT(IY5-IY1))+IX1
      IX1R=IFIX(H1*FLOAT(IY6-IY1))+IX1
      G2=FLOAT(ID3)/FLOAT(ID4)
      IX2L=IFIX(G2*FLOAT(IY5-IY3))+IX3
      IX2R=IFIX(G2*FLOAT(IY6-IY3))+IX3
      IXDL=IX2L-IX1L
      IXDR=IX2R-IX1R
      IF(ISIGN(1,IXDL).EQ.ISIGN(1,IXDR)) GO TO 99
      R=FLOAT(IABS(IXDL))/FLOAT(IABS(IXDR-IXDL))
      IY=IY5+IFIX(R*FLOAT(IY6-IY5))
      IX=IFIX(H1*FLOAT(IY-IY1))+IX1
      NSUC=1
      RETURN
   14 H1=FLOAT(ID1)/FLOAT(ID2)
      IF(ID4.EQ.0) GO TO 15
      G1=FLOAT(ID4)/FLOAT(ID3)
      GH=G1*H1
      IY=(G1*FLOAT(IX1-IX3)-GH*FLOAT(IY1)+FLOAT(IY3))/(1.0-GH)
   17 IX=IFIX(H1*FLOAT(IY-IY1))+IX1
   16 IF((IX.GT.IX6).OR.(IX.LT.IX5)) GO TO 99
      IF((IY.GT.IY6).OR.(IY.LT.IY5)) GO TO 99
      NSUC=1
      RETURN
   15 IY=IY3
      GO TO 17
    1 IF(ID4.NE.0) GO TO 10
      IX=IX1
      IY=IY3
      NSUC=1
      RETURN
    2 IF(ID3.NE.0) GO TO 4
      IX=IX3
      IY=IY1
      NSUC=1
      RETURN
    3 IF(IABS(ID4).EQ.IABS(ID3)) GO TO 99
    4 IF(IABS(ID3).GT.IABS(ID4)) GO TO 12
      H2=FLOAT(ID2)/FLOAT(ID1)
      IF(ID3.EQ.0) GO TO 18
      G2=FLOAT(ID3)/FLOAT(ID4)
      GH=G2*H2
      IX=(G2*FLOAT(IY1-IY3)-GH*FLOAT(IX1)+FLOAT(IX3))/(1.0-GH)
   19 IY=IFIX(H2*FLOAT(IX-IX1))+IY1
```

```
      GO TO 16
   18 IX=IX3
      GO TO 19
   12 H2=FLOAT(ID2)/FLOAT(ID1)
      IY1L=IFIX(H2*FLOAT(IX5-IX1))+IY1
      IY1R=IFIX(H2*FLOAT(IX6-IX1))+IY1
      G1=FLOAT(ID4)/FLOAT(ID3)
      IY2L=IFIX(G1*FLOAT(IX5-IX3))+IY3
      IY2R=IFIX(G1*FLOAT(IX6-IX3))+IY3
      IYDL=IY2L-IY1L
      IYDR=IY2R-IY1R
      IF(ISIGN(1,IYDR).EQ.ISIGN(1,IYDL)) GO TO 99
      R=FLOAT(IABS(IYDL))/FLOAT(IABS(IYDR-IYDL))
      IX=IX5+IFIX(R*FLOAT(IX6-IX5))
      IY=IFIX(H2*FLOAT(IX-IX1))+IY1
      NSUC=1
      RETURN
   99 NSUC=0
      RETURN
      END
```

```
      SUBROUTINE HARD
C--ROUTINE TO MAKE A HARD COPY OF DISPLAY--
      COMMON I1(768),I2(768),LIST(32),
     * LISTC(128),IX(512),IY(512)
      COMMON/HANDY/N,L,IACC
      CALL COPY (ISWIT)        ;SWITCH OFF=4631
      IF(ISWIT .EQ. 0 ) GO TO 5
      DO 1 K=1,L
      IP1=I1(K)
      IP2=I2(K)
      MX=4*IX(IP1)-2047
      MY=4*IY(IP1)-2047
      CALL PLOT(MX,MY,3)
      MX=4*IX(IP2)-2047
      MY=4*IY(IP2)-2047
    1 CALL PLOT(MX,MY,2)
      DO 2 J=1,N
      MX=4*IX(J)-2017
      MY=4*IY(J)-2017
    2 CALL INUM(MX,MY,J,4)
      CALL PLOT(-2047,-2047,3)
  5   CONTINUE
      RETURN
      END
```

NOTE:     PLOT IS THE SUBROUTINE DESCRIBED BY CUNDALL . 974)
FOR PLOTTING THE LINES OR BLOCKS ON AN X-Y R .ORDER

```
      SUBROUTINE CROSS(IX,IY)
      CALL PLOTS(0,IX+10,IY)
      CALL PLOTS(1,IX-10,IY)
      CALL PLOTS(0,IX,IY+10)
      CALL PLOTS(1,IX,IY-10)
      CALL CHARO(159)
      RETURN
      END
```

```
                        .TITL   TEK
                        .ENT    CHARO,CHARI,CURS,PLOTS
                        .EXTD   .FRET,.CPYL
                        .NREL
      177611            N=-167
      177612            N1=N+1
      177613            N2=N1+1
00000'000002            2
00001'006002S CHARO:    JSR     @.CPYL
00002'060277            INTDS
00003'027611            LDA     1,@N,3
00004'044407            STA     1,TWIT
00005'004451            JSR     CHOUT
00006'000013'           TWIT
00007'060177            INTEN
00010'006001S           JSR     @.FRET
00011'000000  TWET:     0
00012'000000  TWOT:     0
00013'000000  TWIT:     0
00014'000000  SV3:      0
00015'000002            2
00016'006002S CHARI:    JSR     @.CPYL
00017'054775            STA     3,SV3
00020'060277            INTDS
00021'004426            JSR     CHIN
00022'000013'           TWIT
00023'024770            LDA     1,TWIT
00024'034770            LDA     3,SV3
00025'047611            STA     1,@N,3
00026'060177            INTEN
00027'006001S           JSR     @.FRET
00030'000004            4
00031'006002S PLOTS:    JSR     @.CPYL
00032'060277            INTDS
00033'027611            LDA     1,@N,3
00034'044757            STA     1,TWIT
00035'027612            LDA     1,@N1,3
00036'044753            STA     1,TWET
00037'027613            LDA     1,@N2,3
00040'044752            STA     1,TWOT
00041'004425            JSR     TPLOT
00042'000013'           TWIT
00043'000011'           TWET
00044'000012'           TWOT
00045'060177            INTEN
00046'006001S           JSR     @.FRET
00047'040416  CHIN:     STA     0,CCAC0 ;SAVE AC0
00050'063610            SKPDN   TTI     ;SKP IF CHAR READY
00051'000777            JMP     .-1
00052'060510            DIAS    0,TTI   ;READ CHAR
00053'043400            STA     0,@0,3  ;STORE CHAR
00054'020411            LDA     0,CCAC0 ;RESTORE ACO
00055'001401            JMP     1,3     ;RETURN
00056'040407  CHOUT:    STA     0,CCAC0 ;SAVE AC0
00057'063511            SKPBZ   TTO     ;SKIP IF NOT BUSY
00060'000777            JMP     .-1
00061'023400            LDA     0,@0,3  ;GET CHARACTER
00062'061111            DOAS    0,TTO   ;SHIP CHARACTER
00063'020402            LDA     0,CCAC0 ;RESTORE AC0
00064'001401            JMP     1,3
```

```
00065'000000  CCAC0:  0                ;TEMP FOR AC0
00066'040526  TPLOT:  STA     0,TPTAC0;SAVE AC0
00067'023401          LDA     0,@1,3   ;GET X
00070'040526          STA     0,TPTX
00071'023402          LDA     0,@2,3   ;GET Y
00072'040525          STA     0,TPTY
00073'023400          LDA     0,@0,3   ;GET MODE
00074'040524          STA     0,TPMOD
00075'054520          STA     3,TPTADD;SAVE CALL ADDRESS
00076'101015          MOV#    0,0,SNR ;SKP IF NEQ 0
00077'000405          JMP     TPTDV    ;= 0  INITIALIZE AND DARK VECTOR
00100'101113          MOVL#   0,0,SNC ;SKIP IF < 0
00101'000405          JMP     TPTNRM   ;NORMAL BRIGHT VECTOR
00102'006511          JSR     @CHOUZ   ;SET TO ALPHA
00103'000202'         US
00104'006507  TPTDV:  JSR     @CHOUZ   ;DARK VECTOR
00105'000201'         GS
00106'020511  TPTNRM: LDA     0,TPTY   ;GET Y
00107'101112          MOVL#   0,0,SZC ;SKP IF +
00110'102400          SUB     0,0      ;MAKE 0
00111'034477          LDA     3,D780   ;UPPER Y BOUND
00112'162513          SUBL#   3,0,SNC ;SKP IF ON SCREEN
00113'161000          MOV     3,0      ;SET TO EDGE
00114'040503          STA     0,TPTY   ;SAVE GOOD Y
00115'101120          MOVZL   0,0      ;USE UPPER 5 BITS
00116'101120          MOVZL   0,0
00117'101120          MOVZL   0,0
00120'101300          MOVS    0,0      ;AND SWAP HALVES
00121'034463          LDA     3,B040   ;HI Y TAG
00122'163000          ADD     3,0      ;PUT IN CHAR
00123'040476          STA     0,TPTTMP;USE A TEMP
00124'006467          JSR     @CHOUZ   ;SHIP HI Y 5
00125'000221'         TPTTMP
00126'020471          LDA     0,TPTY   ;GET Y
00127'034453          LDA     3,B037   ;MASK
00130'163400          AND     3,0      ;LEAVE LOW Y 5
00131'034455          LDA     3,B140   ;LOW Y TAG
00132'163000          ADD     3,0      ;SET IN CHAR
00133'040466          STA     0,TPTTMP
00134'006457          JSR     @CHOUZ   ;SHIP LOW Y
00135'000221'         TPTTMP
00136'020460          LDA     0,TPTX   ;GET X VALUE
00137'101112          MOVL#   0,0,SZC
00140'102400          SUB     0,0
00141'034450          LDA     3,D1023
00142'162513          SUBL#   3,0,SNC
00143'161000          MOV     3,0
00144'040452          STA     0,TPTX
00145'101120          MOVZL   0,0      ;AND DO LIKE Y
00146'101120          MOVZL   0,0
00147'101120          MOVZL   0,0
00150'101300          MOVS    0,0      ;HI X 5
00151'034433          LDA     3,B040   ;HI X TAG
00152'163000          ADD     3,0      ;ADD IN TAG
00153'040446          STA     0,TPTTMP
00154'006437          JSR     @CHOUZ   ;SHIP HI X 5
00155'000221'         TPTTMP
00156'020440          LDA     0,TPTX   ;GET X
00157'034423          LDA     3,B037   ;GOODIE MASK
00160'163400          AND     3,0      ;LEAVE LOW X 5
```

```
00161'034424         LDA     3,B100  ;LOW X TAG
00162'163000         ADD     3,0     ;PUT IN TAG
00163'040436         STA     0,TPTTMP
00164'006427         JSR     @CHOUZ
00165'000221'        TPTTMP
00166'020432         LDA     0,TPMOD
00167'101113         MOVL#   0,0,SNC
00170'000404         JMP     TPTEXT
00171'102400         SUB     0,0
00172'040426         STA     0,TPMOD
00173'000713         JMP     TPTNRM
00174'020420 TPTEXT: LDA     0,TPTAC0;RESTORE AC0
00175'034420         LDA     3,TPTADD;CALL ADDRESS
00176'001403         JMP     3,3     ;EXIT
00177'000032 SUBQQ:  032
00200'000033 ESC:    033
00201'000035 GS:     035
00202'000037 US:     037
00203'000020 B020:   020
      000202' B037=US
00204'000040 B040:   040
00205'000100 B100:   100
00206'000140 B140:   140
00207'000003 D003:   003
00210'001414 D780:   1414
00211'001777 D1023:  1777
00212'000047' CHINP: CHIN
00213'000056' CHOUZ: CHOUT
00214'000000 TPTAC0: 0
00215'000000 TPTADD: 0
00216'000000 TPTX:   0
00217'000000 TPTY:   0
00220'000000 TPMOD:  0
00221'000000 TPTTMP: 0
00222'040772 CURSIS: STA     0,TPTAC0;SAVE AC0
00223'054772         STA     3,TPTADD;SAVE CALL ADDRESS
00224'006767         JSR     @CHOUZ  ;SET TO ALPHA
00225'000202'        US
00226'006765         JSR     @CHOUZ  ;TURN ON CURSER
00227'000200'        ESC
00230'006763         JSR     @CHOUZ
00231'000177'        SUBQQ
00232'006760         JSR     @CHINP  ;GET CHAR
00233'000216'        TPTX
00234'020753         LDA     0,D003  ;GET LOOP COUNTER
00235'040764         STA     0,TPTTMP
00236'020760         LDA     0,TPTX  ;GET CHAR
00237'000421         JMP     CURPS   ;STORE CHAR
00240'006752 CURLP:  JSR     @CHINP  ;GET HI COORD
00241'000216'        TPTX
00242'006750         JSR     @CHINP  ;GET LOW COORD
00243'000217'        TPTY
00244'034736         LDA     3,B037  ;MASK
00245'020752         LDA     0,TPTY  ;LOW COORD
00246'163400         AND     3,0     ;MASK OFF GARBAGE
00247'040750         STA     0,TPTY  ;SAVE FOR LATER
00250'020746         LDA     0,TPTX  ;HI COORD
00251'163400         AND     3,0     ;MASK OFF
00252'101300         MOVS    0,0     ;SWAP
00253'101220         MOVZR   0,0
```

```
00254'101220            MOVER   0,0
00255'101220            MOVER   0,0
00256'034741            LDA     3,TPTY   ;LOW COORD
00257'163000            ADD     3,0      ;ADD IN LOW COORD
00260'034735  CURPS:    LDA     3,TPTADD;CALL ADDRESS
00261'043400            STA     0,@0,3   ;STORE VALUE
00262'175400            INC     3,3      ;ADJUST ADDRESS
00263'054732            STA     3,TPTADD;SAVE UPDATED ADD
00264'014735            DSZ     TPTTMP   ;CHECK FOR DONE
00265'000753            JMP     CURLP    ;LOOP IF NOT
00266'020726            LDA     0,TPTAC0;RESTORE AC0
00267'001400            JMP     0,3      ;RETURN
00270'000004            4
00271'006002S CURS:     JSR     @.CPYL
00272'060277            INTDS
00273'054416            STA     3,SX3
00274'004726            JSR     CURSIS
00275'000312'           A1
00276'000313'           A2
00277'000314'           A3
00300'034411            LDA     3,SX3
00301'024411            LDA     1,A1
00302'047611            STA     1,@N,3
00303'024410            LDA     1,A2
00304'047612            STA     1,@N1,3
00305'024407            LDA     1,A3
00306'047613            STA     1,@N2,3
00307'060177            INTEN
00310'006001S           JSR     @.FRET
00311'000000  SX3:      0
00312'000000  A1:       0
00313'000000  A2:       0
00314'000000  A3:       0
                        .END
```

```
                    .TITL   TAPE
                    .ENT    TAPE, OVLAY
                    .EXTD   .CPYL,.FRET
                    .NREL
      177611        N=-167
00000'000000  NUB:      0
00001'000002  TWO:      2
00002'000003  THREE:    3
00003'000000' FIRST:    NUB
00004'000322' LAST:     C8
00005'000003            3
              ;THIS ROUTINE READS THE APPROPRIATE OVERLAY
              ;FROM TAPE.  IT STARTS BY FIRST TRANSFERING
              ;ITSELF TO A SAFE PLACE IN HIGH CORE.
00006'006001S OVLAY:    JSR     @.CPYL
00007'060277            INTDS
00010'020476            LDA     0,DRIVE
00011'062074            DOB     0,LINC
00012'054473            STA     3,SAVE
00013'023611            LDA     0,@N,3
00014'040764            STA     0,NUB   ;OVERLAY NUMBER
00015'035612            LDA     3,N+1,3 ;ADDR OF LOWEST ARRAY
00016'030765            LDA     2,FIRST
00017'020765            LDA     0,LAST
00020'142400            SUB     2,0     ;=NUMBER OF WORDS TO BE MOVED
00021'101400            INC     0,0
00022'116400            SUB     0,3     ;ADDR TO MOVE TAPE ROUTINE TO
00023'100400            NEG     0,0
00024'025000  ROUND:    LDA     1,0,2
00025'045400            STA     1,0,3
00026'101405            INC     0,0,SNR
00027'000404            JMP     OUT
00030'151400            INC     2,2
00031'175400            INC     3,3
00032'000772            JMP     ROUND
00033'156400  OUT:      SUB     2,3     ;=DISTANCE MOVED
00034'030403            LDA     2,SHIFT
00035'157000            ADD     2,3
00036'001400            JMP     0,3     ; GO TO HI-CORE COPY
00037'000040' SHIFT:    .+1
00040'020740            LDA     0,NUB
00041'126520            SUBZL   1,1
00042'122415            SUB#    1,0,SNR
00043'000407            JMP     A1      ;OVERLAY 1
00044'024735            LDA     1,TWO
00045'122415            SUB#    1,0,SNR
00046'000407            JMP     A2      ;OVERLAY 2
00047'020434            LDA     0,BLK3  ;OVERLAY 3
00050'024434            LDA     1,NBLK3
00051'000406            JMP     CAT
00052'020425  A1:       LDA     0,BLK1
00053'024425            LDA     1,NBLK1
00054'000403            JMP     CAT
00055'020424  A2:       LDA     0,BLK2
00056'024424            LDA     1,NBLK2
00057'152400  CAT:      SUB     2,2
00060'034415            LDA     3,SUBST
00061'054452            STA     3,RETRN
00062'004411            JSR     NIXON
00063'125005            MOV     1,1,SNR
```

```
---
00064'000377            JMP     377      ;FORTRAN START ADDRESS
00065'063077            HALT             ;LINC ERROR
00066'020420            LDA     0,DRIVE ;TRY AGAIN (PRESS CONTINUE)
00067'062074            DOB     0,LINC
00070'000750            JMP     SHIFT+1
00071'060177  NOGO:     INTEN
00072'006002S           JSR     @.FRET
00073'054412  NIXON:    STA     3,SAVE
00074'000445            JMP     RLINC
00075'002752  SUBST:    JMP     @SAVE-RETRN,1 ;SUBSTITUTE CONTENTS FOR 
00076'000000  ORIG:     0
00077'000350  BLK1:     350
00100'000055  NBLK1:    55
00101'000450  BLK2:     450
00102'000037  NBLK2:    37
00103'000510  BLK3:     510
00104'000037  NBLK3:    37
00105'000000  SAVE:     0
00106'000001  DRIVE:    1
00107'000006            6
              ;THIS ROUTINE ENABLES A FORTRAN PROGRAM
              ;TO WRITE BLOCKS OF CORE ONTO TAPE.
              ;
00110'006001S TAPE:     JSR     @.CPYL
00111'060277            INTDS
00112'102400            SUB     0,0
00113'062074            DOB     0,LINC
00114'054771            STA     3,SAVE
00115'023612            LDA     0,@N+1,3
00116'027613            LDA     1,@N+2,3
00117'031614            LDA     2,N+3,3
00120'037611            LDA     3,@N,3
00121'175005            MOV     3,3,SNR
00122'000415            JMP     CLINC
00123'175112            MOVL#   3,3,SZC
00124'000404            JMP     NEGA
00125'175234  DOG:      MOVZR#  3,3,SZR
00126'000415            JMP     WLINC   ;MUST BE 2
00127'000412            JMP     RLINC   ;MUST BE 1
00130'174400  NEGA:     NEG     3,3
00131'150000            COM     2,2
00132'000773            JMP     DOG
00133'034752  RETRN:    LDA     3,SAVE
00134'047615            STA     1,@N+4,3
00135'060177            INTEN
00136'006002S           JSR     @.FRET
              ;NOW FOR A SLIGHTLY MODIFIED VERSION OF THE
              ;STANDARD LINC TAPE UTILITIES....
00137'152400  CLINC:    SUB     2,2
00140'000415            JMP     CHKZ
00141'034426  RLINC:    LDA     3,D2R
00142'000414            JMP     READZ
00143'034422  WLINC:    LDA     3,D1W
00144'054507            STA     3,D1XX
00145'044500            STA     1,D2XX
00146'050416            STA     2,SAC2
00147'004422            JSR     DO
00150'024475  RAW:      LDA     1,D2XX
00151'122400            SUB     1,0
00152'030412            LDA     2,SAC2
```

```
00153'151113            MOVL#     2,2,SNC
00154'150000            COM       2,2
00155'034472  CHK2:     LDA       3,D2C
00156'054467  READ2:    STA       3,D2XX
00157'034407            LDA       3,D1RC
00160'054473            STA       3,D1XX
00161'004410            JSR       DO
00162'060274  EXIT:     NIOC      LINC
00163'000750            JMP       RETRN
00164'000000  SAC2:     0
00165'021000  D1W:      LDA       0,0,2
00166'000750  D1RC:     JMP       READ-D1XX,1
00167'132512  D2R:      SUBL#     1,2,SZC
00170'000000  RETU:     0
00171'054777  DO:       STA       3,RETU
00172'075474            DIB       3,LINC
00173'175112            MOVL#     3,3,SZC
00174'000446            JMP       E4
00175'151113            MOVL#     2,2,SNC
00176'000410            JMP       FINDF
00177'150000            COM       2,2
00200'176400  FINDR:    SUB       3,3
00201'162000            ADC       3,0
00202'060374            NIOP      LINC
00203'004467            JSR       GETBL
00204'101401  FINDN:    INC       0,0,SKP
00205'000776            JMP       .-2
00206'060174  FINDF:    NIOS      LINC
00207'004463            JSR       GETBL
00210'000777            JMP       .-1
00211'175224            MOVZR     3,3,SZR
00212'000766            JMP       FINDR
00213'125005  FOUND:    MOV       1,1,SNR
00214'002754            JMP       @RETU
00215'166000            ADC       3,1
00216'040474            STA       0,TEMP1
00217'044474            STA       1,TEMP2
00220'024476            LDA       1,SIZE
00221'147000            ADD       2,1
00222'000431            JMP       D1XX
00223'063674  READ:     SKPDN     LINC
00224'000777            JMP       .-1
00225'063474            SKPBN     LINC
00226'000416            JMP       RDAT
00227'060474  RCHK:     DIA       0,LINC
00230'116405            SUB       0,3,SNR
00231'000434            JMP       SCHK
00232'024465  E1:       LDA       1,C1
00233'000403            JMP       .+3
00234'034462  E2:       LDA       3,SIZE
00235'024463            LDA       1,C2
00236'020454            LDA       0,TEMP1
00237'000723            JMP       EXIT
00240'024461  E3:       LDA       1,C4
00241'000721            JMP       EXIT
00242'024460  E4:       LDA       1,C8
00243'000717            JMP       EXIT
00244'060474  RDAT:     DIA       0,LINC
00245'132512  D2XX:     SUBL#     1,2,SZC
00246'041000            STA       0,0,2
```

```
00247'000402  D2C:     JMP      .+2
00250'061074  WDAT:    DOA      0,LINC
00251'117000  BLOOP:   ADD      0,3
00252'151400           INC      2,2
00253'021000  DIXX:    LDA      0,0,2
00254'063074           DOC      0,LINC
00255'063674           SKPDN    LINC
00256'000777           JMP      .-1
00257'063474           SKPBN    LINC
00260'000770           JMP      WDAT
00261'075074  WCHK:    DOA      3,LINC
00262'075474           DIB      3,LINC
00263'175004           MOV      3,3,SZR
00264'000756           JMP      E4
00265'132414  SCHK:    SUB#     1,2,SZR
00266'000746           JMP      E2
00267'020423  NEXT:    LDA      0,TEMP1
00270'024423           LDA      1,TEMP2
00271'000713           JMP      FINDN
00272'054420  GETBL:   STA      3,TEMP1
00273'034421           LDA      3,MLIM
00274'162432           SUBZ#    3,0,SZC
00275'000405           JMP      WAIT
00276'034417           LDA      3,PLIM
00277'162032           ADCZ#    3,0,SZC
00300'000740           JMP      E3
00301'074474           DIA      3,LINC
00302'063474  WAIT:    SKPBN    LINC
00303'000777           JMP      WAIT
00304'063774           SKPDZ    LINC
00305'000774           JMP      WAIT-1
00306'074474           DIA      3,LINC
00307'116543           SUBOL    0,3,SNC
00310'010402           ISZ      TEMP1
00311'002401           JMP      @TEMP1
00312'000000  TEMP1:   0
00313'000000  TEMP2:   0
00314'177770  MLIM:    177770
00315'000620  PLIM:    620
00316'000400  SIZE:    400
00317'000001  C1:      1
00320'000002  C2:      2
00321'000004  C4:      4
00322'000010  C8:      10
                       .END
```

```
                        .TITL   COPY
                        .ENT    COPY
                        .EXTD   .CYPL,.FRET
                        .NREL
      177611            N=-167
00000'000002            2
00001'006001S COPY:     JSR     @.CYPL
00002'054422            STA     3,ACSV
00003'060477            READS   0       ;CHECK FOR SWITCH 0
00004'101122            MOVZL   0,0,SZC ;OFF=4631 ON=PLOTTER
00005'000414            JMP     PLTR
00006'020417            LDA     0,ESC
00007'063511            SKPBZ   TTO
00010'000777            JMP     .-1
00011'061111            DOAS    0,TTO
00012'020414            LDA     0,ETB
00013'063511            SKPBZ   TTO
00014'000777            JMP     .-1
00015'061111            DOAS    0,TTO
00016'102440            SUBO    0,0
00017'043611            STA     0,@N,3  ;PUT A ZERO SO HARD SKIPS
00020'000403            JMP     BACK
00021'102520  PLTR:     SUBZL   0,0     ;PUT A ONE TO PLOT
00022'043611            STA     0,@N,3
00023'006002S BACK:     JSR     @.FRET
              ;
00024'000000  ACSV:     0
00025'000033  ESC:      27.
00026'000027  ETB:      23.
              ;
                        .END
```

---

```
                        .TITL   OVLAP
                        .ENT    OVLAP
                        .EXTD   .CPYL,.FRET
                        .NREL
       177611           N=-167
       177612           N1=N+1
       177613           N2=N+2
       177614           N3=N+3
       177615           N4=N+4
       177616           N5=N+5
       177617           N6=N+6
00000'000000   SAVE:    0
00001'000000   X5:      0
00002'000000   X6:      0
00003'000010            10
00004'006001S  OVLAP:   JSR     @.CPYL
00005'054773            STA     3,SAVE
00006'023611            LDA     0,@N,3
00007'027612            LDA     1,@N1,3
00010'033613            LDA     2,@N2,3
00011'037614            LDA     3,@N3,3
00012'122512            SUBL#   1,0,SZC
00013'000455            JMP     F1
00014'172512            SUBL#   3,2,SZC
00015'000426            JMP     F2
00016'162513            SUBL#   3,0,SNC
00017'132512            SUBL#   1,2,SZC
00020'000533            JMP     NOGO
00021'112512            SUBL#   0,2,SZC
00022'000411            JMP     F3
00023'136512            SUBL#   1,3,SZC
00024'000404            JMP     F4
00025'054754            STA     3,X5
00026'040754            STA     0,X6
00027'000514            JMP     OK
00030'044751   F4:      STA     1,X5
00031'040751            STA     0,X6
00032'000511            JMP     OK
00033'136512   F3:      SUBL#   1,3,SZC
00034'000404            JMP     F5
00035'054744            STA     3,X5
00036'050744            STA     2,X6
00037'000504            JMP     OK
00040'044741   F5:      STA     1,X5
00041'050741            STA     2,X6
00042'000501            JMP     OK
00043'142513   F2:      SUBL#   2,0,SNC
00044'136512            SUBL#   1,3,SZC
00045'000506            JMP     NOGO
00046'116512            SUBL#   0,3,SZC
00047'000411            JMP     F6
00050'132512            SUBL#   1,2,SZC
00051'000404            JMP     F7
00052'050727            STA     2,X5
00053'040727            STA     0,X6
00054'000467            JMP     OK
00055'044724   F7:      STA     1,X5
00056'040724            STA     0,X6
00057'000464            JMP     OK
00060'132512   F6:      SUBL#   1,2,SZC
```

```
00061'000404           JMP     F8
00062'050717           STA     2,X5
00063'054717           STA     3,X6
00064'000457           JMP     OK
00065'044714  F8:      STA     1,X5
00066'054714           STA     3,X6
00067'000454           JMP     OK
00070'172512  F1:      SUBL#   3,2,SZC
00071'000426           JMP     F9
00072'166513           SUBL#   3,1,SNC
00073'112512           SUBL#   0,2,SZC
00074'000457           JMP     NOGO
00075'132512           SUBL#   1,2,SZC
00076'000411           JMP     F10
00077'116512           SUBL#   0,3,SZC
00100'000404           JMP     F11
00101'054700           STA     3,X5
00102'044700           STA     1,X6
00103'000440           JMP     OK
00104'040675  F11:     STA     0,X5
00105'044675           STA     1,X6
00106'000435           JMP     OK
00107'116512  F10:     SUBL#   0,3,SZC
00110'000404           JMP     F12
00111'054670           STA     3,X5
00112'050670           STA     2,X6
00113'000430           JMP     OK
00114'040665  F12:     STA     0,X5
00115'050665           STA     2,X6
00116'000425           JMP     OK
00117'146513  F9:      SUBL#   2,1,SNC
00120'116512           SUBL#   0,3,SZC
00121'000432           JMP     NOGO
00122'136512           SUBL#   1,3,SZC
00123'000411           JMP     F13
00124'112512           SUBL#   0,2,SZC
00125'000404           JMP     F14
00126'050653           STA     2,X5
00127'044653           STA     1,X6
00130'000413           JMP     OK
00131'040650  F14:     STA     0,X5
00132'044650           STA     1,X6
00133'000410           JMP     OK
00134'112512  F13:     SUBL#   0,2,SZC
00135'000404           JMP     F15
00136'050643           STA     2,X5
00137'054643           STA     3,X6
00140'000403           JMP     OK
00141'040640  F15:     STA     0,X5
00142'054640           STA     3,X6
00143'020636  OK:      LDA     0,X5
00144'024636           LDA     1,X6
00145'034633           LDA     3,SAVE
00146'043615           STA     0,@N4,3
00147'047616           STA     1,@N5,3
00150'102520           SUBZL   0,0
00151'043617           STA     0,@N6,3
00152'006002S          JSR     @.FRET
00153'034625  NOGO:    LDA     3,SAVE
00154'102460           SUBC    0,0
```

```
---
 00155'043617          STA     0,@N6,3
 00156'006002$         JSR     @.FRET
                       .END
---
```

```
                        .TITL   DIGIT
                        .ENT    DIGIT
                        .EXTD   .CPYL,.FRET
               ;----------------------------------------
               ;
               ;    FORTRAN INTERFACED DIGITIZER ROUTINE
               ;    AS CREATED BY PAC --
               ;    MODIFIED MAR. 8,1976 TO ACCOMODATE ANALOG
               ;
               ;----------------------------------------
                        .NREL
         177611 N=-167
         000041 DVCE=41          ;NO LONGER DEVICE 42
00000'002400    MODE:   2400
00001'000004            4
00002'006001S   DIGIT:  JSR     @.CPYL
00003'060277            INTDS
00004'020774            LDA     0,MODE
00005'062041            DOB     0,DVCE
00006'000457            JMP     BACK
00007'063710    LOOP:   SKPDZ   TTI
00010'000466            JMP     HIT
00011'020476            LDA     0,CH3     ;NO LONGER CHANNEL 0
00012'061041            DOA     0,DVCE
00013'063641            SKPDN   DVCE
00014'000777            JMP     .-1
00015'060441            DIA     0,DVCE
00016'024466            LDA     1,C1000
00017'106513            SUBL#   0,1,SNC
00020'000767            JMP     LOOP
00021'020464            LDA     0,CH1
00022'061041            DOA     0,DVCE    ;GET X
00023'063641            SKPDN   DVCE
00024'000777            JMP     .-1
00025'060441            DIA     0,DVCE
00026'043611            STA     0,@N,3
00027'020457            LDA     0,CH2
00030'061041            DOA     0,DVCE
00031'063641            SKPDN   DVCE
00032'000777            JMP     .-1
00033'060441            DIA     0,DVCE
00034'043612            STA     0,@N+1,3
00035'102400            SUB     0,0
00036'043613            STA     0,@N+2,3          ;ZERO FOR ICODE
00037'020422            LDA     0,MAX
00040'024422            LDA     1,CHLMP ;ROUTINE TO FLASH LAMP
00041'063634            SKPDN   34      ;WHEN ACKNOWLEDGING DATA
00042'000777            JMP     .-1     ;INTO BLOCKS PROGRAM
00043'066034            DOB     1,34
00044'061034            DOA     0,34
00045'020416            LDA     0,DEL
00046'040416            STA     0,COUNT
00047'060000    DELAY:  NIO     0
00050'060000            NIO     0
00051'014413            DSZ     COUNT
00052'000775            JMP     DELAY
00053'102400            SUB     0,0
00054'024406            LDA     1,CHLMP
00055'066034            DOB     1,34
00056'061034            DOA     0,34
```

AD-A084 693 MINNESOTA UNIV MINNEAPOLIS DEPT OF CIVIL AND MINING --ETC F/G 13/2
RATIONAL DESIGN OF TUNNEL SUPPORTS: AN INTERACTIVE GRAPHICS BAS--ETC(U)
SEP 79 M D VOEGELE DACW45-74-C-0066
UNCLASSIFIED WES/TR/GL-79-15 NL

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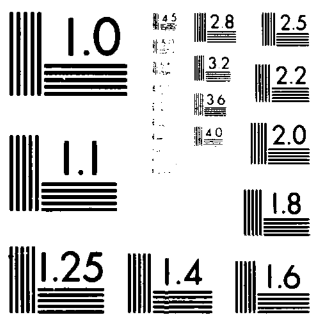


MICROCOPY RESOLUTION TEST CHART

```
00057'060177              INTEN
00060'006002S             JSR      @.FRET
00061'003777  MAX:        3777     ;MAX VOLTAGE IS 5 VOLTS
00062'000002  CHLMP:      2        ; LAMP CHANNEL IS #2
00063'050000  DEL:        50000    ;APPROX. 0.15 SEC DELAY (LAMP ON)
00064'000000  COUNT:      0
              ;HANG ON UNTIL BUTTON VOLTAGE
              ;IS LESS THAN 2.5 VOLTS
00065'020422  BACK:       LDA      0,CH3    ;NO LONGER CHANNEL 0
00066'061041              DOA      0,DVCE
00067'063641              SKPDN    DVCE
00070'000777              JMP      .-1
00071'060441              DIA      0,DVCE
00072'024412              LDA      1,C1000
00073'106512              SUBL#    0,1,SZC
00074'000771              JMP      BACK
00075'000712              JMP      LOOP
00076'024412  HIT:        LDA      1,MASK
00077'060510              DIAS     0,TTI
00100'123400              AND      1,0
00101'043613              STA      0,@N+2,3
00102'060177              INTEN
00103'006002S             JSR      @.FRET
00104'001000  C1000:      1000
00105'000020  CH1:        20
00106'000040  CH2:        40
00107'000060  CH3:        60
00110'000177  MASK:       177
                          .END
```

```
C--------SECOND OVERLAY--------
C--ROUTINE TO BUILD BLOCKS FROM LINES
      COMMON KEY(256),IBLOC(1536),IDUM(608),I1(768),
     *  I2(768),LIST(32),LISTC(128),IX(512),IY(512)
      COMMON/HANDY/N,L,IACC
C
C     N=NUMBER OF POINTS
C     L=NUMBER OF LINES
C
      N=LIST(1)
      L=LIST(2)
      IACC=LIST(3)
      IF(L.LE.2) GOTO 18
      PI=4.0*ATAN(1.0)
      PI2=2.0*PI
      PI05=0.5*PI
      PI180=PI/360.
      LBIT=100000K
      MASK=77777K
      K=1
      NBLOC=0
C--SET FLAGS ON ALL LINES--
      DO 1 LL=1,L
      I1(LL)=I1(LL).OR.LBIT
    1 I2(LL)=I2(LL).OR.LBIT
C--FIND IF ANY FLAGS STILL LEFT--
    2 DO 3 LL=1,L
      IF(I1(LL).AND.LBIT) GOTO 4
      IF(I2(LL).AND.LBIT) GOTO 5
    3 CONTINUE
      IF(NBLOC.GT.0) GOTO 17
   18 CALL OVLAY(1,KEY)
      PAUSE
      GOTO 18
   17 KEY(NBLOC+1)=K  ;ALL FLAGS MUST BE DOWN.
      CALL CHARO(135) ;FIND CENTROIDS ETC.
      CALL CENT(NBLOC)
    4 I1(LL)=I1(LL).AND.MASK
      IEND1=I1(LL)
      IEND2=I2(LL).AND.MASK
      GO TO 6
    5 I2(LL)=I2(LL).AND.MASK
      IEND1=I2(LL)
      IEND2=I1(LL)     ;(FLAG MUST ALREADY BE DOWN)
    6 ISTART=IEND1
      IPNT=1
      LISTC(1)=LL
      GAMSUM=0.0
      IXD=IX(IEND2)-IX(IEND1)
      IYD=IY(IEND2)-IY(IEND1)
      IF(IXD.NE.0) GOTO 8
      IF(IYD.LT.0) GOTO 7
      ALFOLD=PI/2.0
      GOTO 9
    7 ALFOLD=1.5*PI
```

```
      GOTO 9
    8 ALFOLD=ATAN(ABS(FLOAT(IYD)/FLOAT(IXD)))
      IF(IXD.LT.0) GOTO 10
      IF(IYD.GT.0) GOTO 9
      ALFOLD=PI2-ALFOLD
      GOTO 9
   10 IF(IYD.GT.0) GOTO 11
      ALFOLD=ALFOLD+PI
      GOTO 9
   11 ALFOLD=PI-ALFOLD
C--FIND MOST CLOCKWISE LINE FROM LL--
    9 LMAX=0
      GAMAX=PI
      DO 12 LIN=1,L
      IF(LIN.EQ.LL) GOTO 12
      IF(I1(LIN).AND.LBIT) GOTO 13
   16 IF(I2(LIN).AND.LBIT) GOTO 14
      GOTO 12
   13 IF((I1(LIN).AND.MASK).NE.IEND2) GOTO 16
      IE1=IEND2
      IE2=I2(LIN).AND.MASK
      GOTO 15
   14 IF((I2(LIN).AND.MASK).NE.IEND2) GOTO 12
      IE1=IEND2
      IE2=I1(LIN).AND.MASK
   15 IXD=IX(IE2)-IX(IE1)
      IYD=IY(IE2)-IY(IE1)
      IF(IXD.NE.0) GOTO 20
      IF(IYD.LT.0) GOTO 19
      ALF=PI/2.0
      GOTO 22
   19 ALF=1.5*PI
      GOTO 22
   20 ALF=ATAN(ABS(FLOAT(IYD)/FLOAT(IXD)))
      IF(IXD.LT.0) GOTO 21
      IF(IYD.GT.0) GOTO 22
      ALF=PI2-ALF
      GOTO 22
   21 IF(IYD.GT.0) GOTO 23
      ALF=ALF+PI
      GOTO 22
   23 ALF=PI-ALF
   22 GAM=ALF-ALFOLD
      IF(GAM.GE.PI) GAM=GAM-PI2
      IF(GAM.LT.-PI)GAM=GAM+PI2
      IF(GAM.GE.GAMAX) GOTO 12
      GAMAX=GAM        ;MOST CLOCKWISE ANGLE YET...
      LMAX=LIN         ;..WITH ITS CORRESPONDING LINE.
      ALFMAX=ALF
      IED1=IE1
      IED2=IE2
   12 CONTINUE
      IF(LMAX.EQ.0) GOTO 28   ;DEAD END !
C--KNOCK DOWN FLAG FOR THAT LINE--
      IF((I1(LMAX).AND.MASK).EQ.IED2) GOTO 24
```

```
      I1(LMAX)=IED1
      GOTO 25
   24 I2(LMAX)=IED1
   25 GAMSUM=GAMSUM+GAMAX      ;SUM OF ALL BLOCK ANGLES
      IPNT=IPNT+1      ;POINTER TO TEMP. LIST OF LINES
      LISTC(IPNT)=LMAX
      IF(IED2.EQ.ISTART) GOTO 26
      LL=LMAX          ;NEW LINE BECOMES OLD LINE
      ALFOLD=ALFMAX
      IEND2=IED2
      GOTO 9
   26 IF(GAMSUM.GT.0.0)GOTO 2
      NBLOC=NBLOC+1
      KEY(NBLOC)=K
C--THE NEXT SECTION MERGES ADJACENT LINES IF
C--THEY HAVE NEARLY EQUAL SLOPES, AND WRITES
C--THE RESULTING LIST OF POINTS ONTO IBLOC( )
      LINE=LISTC(1)
      IF(ISTART.EQ.I1(LINE)) GOTO 31
      IP1=I1(LINE).AND.MASK
      GOTO 32
   31 IP1=I2(LINE).AND.MASK
   32 IX1=IX(IP1)
      IY1=IY(IP1)
      IX0=IX(ISTART)
      IY0=IY(ISTART)
      IXD=IX1-IX0
      IYD=IY1-IY0
      IF(IXD.EQ.0) GOTO 43
      ALF1=ATAN2(FLOAT(IYD),FLOAT(IXD))
      GOTO 44
   43 ALF1=SIGN(PI05,FLOAT(IY1))
   44 ALF1R=ALF1
      DO 50 IK=2,IPNT
      IF(IK.EQ.IPNT) GOTO 51
      LINE=LISTC(IK)
      IF(IP1.EQ.I1(LINE)) GOTO 41
      IP2=I1(LINE).AND.MASK
      GOTO 42
   41 IP2=I2(LINE).AND.MASK
   42 IX2=IX(IP2)
      IY2=IY(IP2)
   47 IXD=IX2-IX1
      IYD=IY2-IY1
      IF(IXD.EQ.0) GOTO 45
      ALF2=ATAN2(FLOAT(IYD),FLOAT(IXD))
      GOTO 46
   45 ALF2=SIGN(PI05,FLOAT(IY2))
   46 IF(ABS(ALF2-ALF1).LT.PI180) GOTO 53
      IBLOC(K)=IP1
      K=K+1
      IP1=IP2
      ALF1=ALF2
      IX1=IX2
      IY1=IY2
```

```
      GOTO 50
51    IX2=IX(ISTART)
      IY2=IY(ISTART)
      GOTO 47
53    IP1=IP2
50    CONTINUE
C--LAST LINE TO DO NOW--
      IF(ABS(ALF1R-ALF1).LT.PI180) GOTO 48
      IBLOC(K)=ISTART
      K=K+1
48    IF(K-KEY(NBLOC).GT.2) GOTO 52
C--WEED OUT THIN BLOCKS--
      K=KEY(NBLOC)
      NBLOC=NBLOC-1
      GOTO 2
52    K1=KEY(NBLOC)
      K2=K-1
      CALL PLOTS(0,IX(IBLOC(K2)),IY(IBLOC(K2)))
      DO 49 KB=K1,K2
49    CALL PLOTS(1,IX(IBLOC(KB)),IY(IBLOC(KB)))
      GOTO 2
C--DEAL WITH DEAD END--
28    I1(LL)=I1(LL).AND.MASK
      I2(LL)=I2(LL).AND.MASK
      IF(IPNT.LE.1) GOTO 2
      IPNM=IPNT-1
      ITO=ISTART
C--RESTORE FLAGS TO PRECEEDING LINES--
      DO 30 IL=1,IPNM
      LINE=LISTC(IL)
      IF(ITO.EQ.I1(LINE)) GOTO 33
      ITO=I1(LINE).AND.MASK
      I2(LINE)=I2(LINE).OR.LBIT
      GOTO 30
33    ITO=I2(LINE).AND.MASK
      I1(LINE)=I1(LINE).OR.LBIT
30    CONTINUE
      GOTO 2
      END
```

```
      SUBROUTINE CENT(NBLOC)
C--TO FIND THE AREAS AND CENTROIDS OF ALL BLOCKS
      COMMON KEY(256),IBLOC(1536),LENG(1536),IAREA(256),
     *  ICX(256),ICY(256),IX(512),IY(512)
      COMMON/HANDY/N,L,IACC
      AMIN=IACC*IACC*5
      DO 1 N=1,NBLOC
      K1=KEY(N)
      K2=KEY(N+1)-1
C--FIND LOWER LEFT-HAND CORNER--
      IXM=1023
      IYM=780
      DO 3 K=K1,K2
      IP=IBLOC(K)
      IF(IX(IP).LT.IXM) IXM=IX(IP)
      IF(IY(IP).LT.IYM) IYM=IY(IP)
    3 CONTINUE
C--FIND BLOCK AREAS--
      AREA1=0.0
      AREA2=0.0
      IP1=IBLOC(K2)
      DO 2 K=K1,K2
      IP2=IBLOC(K)
      IX1=IX(IP1)-IXM
      IX2=IX(IP2)-IXM
      IY2=IY(IP2)-IYM
      IY1=IY(IP1)-IYM
      AREA1=AREA1+FLOAT(IX2-IX1)*FLOAT(IY1+IY2)/2.0
      AREA2=AREA2+FLOAT(IY2-IY1)*FLOAT(IX1+IX2)/2.0
    2 IP1=IP2
      AREA=(AREA1-AREA2)/2.0
      IF(AREA.LE.AMIN) GOTO 13
      IAREA(N)=AREA/AMIN
C--NOW FIND MOMENTS OF AREAS ABOUT IXM, IYM--
      XM=0.0
      YM=0.0
      IP1=IBLOC(K2)
      DO 12 K=K1,K2
      IP2=IBLOC(K)
      IX1=IX(IP1)-IXM
      IX2=IX(IP2)-IXM
      IY1=IY(IP1)-IYM
      IY2=IY(IP2)-IYM
      F1=FLOAT(IX2-IX1)/2.0
      F2=FLOAT(IX2+IX1)
      IF(IY2-IY1) 5,6,7
    6 XM=XM+F1*F2*FLOAT(IY1)
      GOTO 8
    5 XM=XM+F1*(F2*FLOAT(IY2)+FLOAT(IY1-IY2)*FLOAT(2*IX1+IX2)/3.0)
      GOTO 8
    7 XM=XM+F1*(F2*FLOAT(IY1)+FLOAT(IY2-IY1)*FLOAT(IX1+IX2*2)/3.0)
    8 G1=FLOAT(IY2-IY1)/2.0
      G2=FLOAT(IY2+IY1)
      IF(IX2-IX1) 9,10,11
   10 YM=YM-G1*G2*FLOAT(IX1)
```

```
          GOTO 12
      9   YM=YM-G1*(G2*FLOAT(IX2)+FLOAT(IX1-IX2)*FLOAT(IY2+2*IY1)/3.0)
          GOTO 12
     11   YM=YM-G1*(G2*FLOAT(IX1)+FLOAT(IX2-IX1)*FLOAT(IY1+2*IY2)/3.0)
     12   IP1=IP2
          ICX(N)=IFIX(XM/AREA+0.5)+IXM
          ICY(N)=IFIX(YM/AREA+0.5)+IYM
          CALL CROSS(ICX(N),ICY(N))
          GOTO 1
     13   IAREA(N)=0.0
      1   CONTINUE
C--TO COMPUTE THE LENGTHS OF EACH EDGE--
          DO 80 N=1,NBLOC
          K1=KEY(N)
          K2=KEY(N+1)-1
          IPA=IBLOC(K2)
          KN=K2
          DO 81 K=K1,K2
          IPB=IBLOC(K)
          XDIF=IX(IPB)-IX(IPA)
          YDIF=IY(IPB)-IY(IPA)
          LENG(KN)=SQRT(XDIF*XDIF+YDIF*YDIF) + 0.5
          KN=K
     81   IPA=IPB
     80   CONTINUE
C--------------------------------------
     25   CALL CURS(ID,IXX,IYY)
          CALL CHARO(159)
          IF(ID.EQ.197) GOTO 20   ;"E" FOR "ERASE"
          IF(ID.EQ.200) GOTO 30   ;"H" FOR "HARD COPY"
          IF(ID.EQ.208) GOTO 50   ;"P" FOR "PHASE..."
          IF(ID.EQ.193) GOTO 22   ;"A" FOR "ALL"
          IF(ID.EQ.211) GOTO 60   ;"S" FOR "SINGLE"
          IF(ID.EQ.210) GOTO 70   ;"R" FOR "RESTORE"
          GOTO 25
     20   DO 24 N=1,NBLOC
          IF(IABS(ICX(N)-IXX).GT.IACC) GOTO 24
          IF(IABS(ICY(N)-IYY).GT.IACC) GOTO 24
          IF(IAREA(N).LE.0) GOTO 24
          IAREA(N)=-IAREA(N)
          GOTO 22
     24   CONTINUE
          GOTO 25
     22   CALL CHARO(155)
          CALL CHARO(140)
          DO 21 N=1,NBLOC
          IF(IAREA(N).LE.0) GOTO 21
          K1=KEY(N)
          K2=KEY(N+1)-1
          CALL PLOTS(0,IX(IBLOC(K2)),IY(IBLOC(K2)))
          DO 23 K=K1,K2
     23   CALL PLOTS(1,IX(IBLOC( K)),IY(IBLOC( K)))
          CALL CROSS(ICX(N),ICY(N))
     21   CONTINUE
          GOTO 25
```

```
30    CALL COPY (ISWIT)        ;CHECK FOR SWITCH
      IF(ISWIT .EQ. 0 )  GO TO 25
      DO 31 N=1,NBLOC
      IF(IAREA(N).LE.0) GOTO 31
      K1=KEY(N)
      K2=KEY(N+1)-1
      I1=IX(IBLOC(K2))*4-2047
      I2=IY(IBLOC(K2))*4-2047
      CALL PLOT(I1,I2,3)
      DO 32 K=K1,K2
      I1=IX(IBLOC(K))*4-2047
      I2=IY(IBLOC(K))*4-2047
32    CALL PLOT(I1,I2,2)
      IC1=ICX(N)*4
      IC2=ICY(N)*4
      CALL PLOT(IC1-2087,IC2-2047,3)
      CALL PLOT(IC1-2007,IC2-2047,2)
      CALL PLOT(IC1-2047,IC2-2087,3)
      CALL PLOT(IC1-2047,IC2-2007,2)
31    CONTINUE
      CALL PLOT(-2047,-2047,3)
      GOTO 25
40    CALL CHARO(155)
      CALL CHARO(140)
      CALL OVLAY(1,KEY)
      GOTO 25
50    CALL CHARI(IN)
      IF(IN.EQ.177) GOTO 40    ;"1" FOR "PHASE 1"
      IF(IN.NE.179) GOTO 25    ;"3" FOR "PHASE 3"
      CALL CHARO(155)
      CALL CHARO(140)
      IBLOC(1536)=NBLOC
      CALL OVLAY(3,KEY)
      GOTO 25
60    DO 61 N=1,NBLOC
      IF(IABS(ICX(N)-IXX).GT.IACC) GOTO 61
      IF(IABS(ICY(N)-IYY).GT.IACC) GOTO 61
      GOTO 62
61    CONTINUE
      GOTO 25
62    NN=N
      IF(IAREA(NN).LE.0) GOTO 25
      CALL CHARO(155)
      CALL CHARO(140)
      K1=KEY(NN)
      K2=KEY(NN+1)-1
      CALL PLOTS(0,IX(IBLOC(K2)),IY(IBLOC(K2)))
      DO 63 K=K1,K2
63    CALL PLOTS(1,IX(IBLOC(K)),IY(IBLOC(K)))
      CALL CROSS(ICX(NN),ICY(NN))
      CALL CHARI(IN)
      IF(IN.NE.197) GOTO 22
      IAREA(NN)=-IABS(IAREA(NN))
      GOTO 22
70    DO 71 N=1,NBLOC
```

```
      IF(IAREA(N).GE.Ø) GOTO 71
      IAREA(N)=IABS(IAREA(N))
71    CONTINUE
      GOTO 22
      END
```

List of Phase 3 Global Symbols

| Symbol Name | Originating Routine | Purpose of Symbol |
|---|---|---|
| CONTR | CONTR | Iteration and Control routine entry |
| FEET | INPUT | ASCII Length Descriptor |
| MOVFL | INPUT | Memory overflow message |
| MU | FORD | Default value of friction coefficient |
| OPTIN | CYCLE | Pointer to option input routine |
| POUND | INPUT | ASCII force descriptor |
| PUP | REBOX | Pressure segment test entry |
| TRANS | TRANS | Initial translation routine entry |
| .ALLB | UPDAT | Pointer to routine to update all blocks |
| .ALPH | UTIL | Pointer to routine to set Tektronix in alpha mode |
| .AXIS | UTIL | Pointer to routine to draw axes on screen |
| .BSIZ | TRANS | Number of words in block data arrays, excluding corners |
| .C100 | CONTR | A constant (=100 octal) |
| .CHEK | UTIL | Pointer to routine check if character is a digit |
| .CLNC | TAPE | Pointer to tape checking routine |
| .CPNT | UPDAT | Pointer to word that can be changed |
| .CURS | TEK | Pointer to routine that enables cursor |
| .DBØ | UTIL | Pointer to Decimal to Binary conversion routine |
| .DBIN | UTIL | Pointer to Decimal to Binary conversion routine |
| .DCM | MOUIT | Pointer to routine to move a fixed block |
| .DISB | DISPL | Pointer to routine that plots a single block |
| .DISP | DISPL | Pointer to routine that plots all blocks on paper |
| .DISS | DISPL | Pointer to routine that plots all blocks on screen |
| .DMBN | INPUT | Block number of fixed block to be moved |
| .DMBP | INPUT | Block data pointer of fixed block to be moved |
| .EMPT | TRANS | Head of empty list |
| .FORD | FORD | Pointer to force/displacement routine |
| .GETT | UTIL | Pointer to routine to accept keyboard character |
| .HEAV | LOADS | Pointer to routine to modify block weights |
| .HITC | UTIL | Pointer to routine to detect cursor hit on block |
| .HITS | HITS | Pointer to routine to detect cursor hit on edge |
| .IACC | UTIL | Accuracy limit for hits on centroids |

| | | |
|---|---|---|
| .INP | INPUT | Pointer to friction input routine |
| .IPRN | UTIL | Pointer to binary to decimal conversion routine |
| .KET | CYCLE | Pointer to routine to calculate kinetic energy |
| .LENG | UTIL | Pointer to routine to return length of an edge |
| .LODE | INPUT | Pointer to routine for numerical applied load input |
| .LPAP | CONTR | Flag for hard copy load plot option |
| .LPLS | DISPL | Pointer to routine for plotting loads on screen |
| .M1 | TRANS | Pointer to start of block data pointers |
| .M2 | TRANS | Pointer to start of block data arrays |
| .M3 | TRANS | Pointer to start of boxes |
| .M4 | TRANS | Pointer to start of linked lists of block corners |
| .M5 | TRANS | Pointer to start of block pointers to contact lists |
| .M6 | TRANS | Pointer to start of linked list area |
| .M7 | TRANS | Pointer to start of free memory |
| .MEM | TRANS | Highest memory location |
| .MESS | UTIL | Pointer to routine that prints messages on screen |
| .MFLG | INPUT | Flag for displacement control option |
| .MOT | MOTIO | Pointer to law of motion routine |
| .MOVE | INPUT | Pointer to input routine for moving fixed block |
| .MSKR | REBOX | A constant (377 octal) |
| .NUM | TRANS | Total number of blocks |
| .NVEC | DISPL | Flag for printing vector magnitudes |
| .OVL | TAPE | Pointer to routine to read first overlay |
| .PAGE | UTIL | Pointer to routine that clears the screen |
| .PEMT | INPUT | Head of pressure segment empty list |
| .PFLG | CONTR | Flag to control plotting when running |
| .PLTS | TEK | Pointer to line drawing routine entry |
| .PON1 | PONT | Pointer to routine that returns global coordinates |
| .PON2 | PONT | Pointer to quick entry to above routine |
| .PRES | INPUT | Head of pressure segment list |
| .PRN1 | UTIL | Pointer to routine that prints a single character |
| .PRN2 | UTIL | Pointer to routine that prints character in ACØ |
| .PSEG | INPUT | Pointer to pressure segment input routine |
| .PSIZ | TRANS | Number of words in each contact entry |
| .READ | TAPE | Pointer to routine to read a stored data set |
| .REBX | REBOX | Pointer to re-boxing routine entry |
| .REBZ | REBOX | Pointer to re-boxing routine, alternate entry |

| | | |
|---|---|---|
| .RLNC | TAPE | Pointer to tape reading routine |
| .ROT | MOTIO | Constant of integration for angular velocity |
| .RSET | CYCLE | Pointer to routine that resets cycle counter |
| .SCAL | UTIL | Pointer to vector scaling routine |
| .SING | UPDAT | Pointer to single block updating routine |
| .SPRP | INPUT | Pointer to beginning of friction table |
| .STEP | CYCLE | Pointer to routine to increment cycle counter |
| .SYCL | INPUT | Frequency of movement of fixed block |
| .TIME | FORD | Pointer to routine to change time step |
| .TPRN | CYCLE | Pointer to routine that displays cycles |
| .TREC | MOTIO | Inverse time step |
| .TYP | UTIL | Pointer to return surface type number for edge |
| .UD | INPUT | Unit of displacement |
| .UINP | INPUT | Pointer to units input routine |
| .UREP | CONTR | Update frequency |
| .UW | INPUT | Unit weight |
| .VEC | CONTR | Vector plotting flag |
| .VFAC | UTIL | Vector scaling factor |
| .WLNC | TAPE | Pointer to tape writing routine |
| .WORD | UTIL | Pointer to routine to get alphanumeric string |
| .WRIT | TAPE | Pointer to routine to store a data set |
| .XCGD | INPUT | X - component of fixed block displacement |
| .YCGD | INPUT | Y component of fixed block displacement |

```
                        .TITL   TRANS
                ;TO CREATE NEW DATA STRUCTURES FROM
                ;THE ORIGINAL FORTRAN ARRAYS.
                        .ENT    TRANS,.M1,.M2,.M3,.NUM,.BSIZ
                        .ENT    .M4,.M5,.M6,.M7,.EMPT,.PSIZ
                        .ENT    .MEM
                        .EXTN   CONTR
                        .EXTD   .PON1,.PON2,.ALLB,.DISS,.MSKR
                        .EXTD   .OVL,.MESS,.TPRN
                        .ZREL
00000-000000    .MEM:   0       ;HIGHEST MEMORY LCTN
00001-000000    .M1:    0
00002-000000    .M2:    0
00003-000000    .M3:    0
00004-000000    .M4:    0       ;LINK ARRAY START
00005-000000    .M5:    0       ;LINK ARRAY END+1
00006-000000    .M6:    0
00007-000000    .M7:    0       ;NEXT FREE CORE LOCATION
00010-000000    .EMPT:  0       ;NEXT EMPTY LIST START
00011-000014    .PSIZ:  14      ;PROD ENTRY SIZE
00012-000000    .NUM:   0       ;NUMBER OF BLOCKS
00013-000025    .BSIZ:  25      ;START OF POINT DATA
                        .NREL
00000'000000    AREA:   0       ;FORTRAN COMMON LOCATIONS
00001'000000    ICX:    0
00002'000000    ICY:    0
00003'000000    KEY:    0
00004'000000    LENG:   0
00005'000404    NMAX:   404     ;TOP OF PROGRAM AREA
00006'000400    F400:   400
00007'000417'   NEXTR:  NEXT
      000012            .RDX    10
                ;FOLLOWING SIZES MUST BE CHANGED IF
                ;COMMON BLOCK IS CHANGED IN THE
                ;FORTRAN PROGRAMS, PHASES 1 & 2
00010'000011'   TBL:    .+1
00011'001001            513     ;IY     )
00012'001000            512     ;IX     )
00013'000400            256     ;ICY    )
00014'000400            256     ;ICX    )
00015'000400            256     ;IAREA  )  FORT. ARRAY NAMES
00016'003000            1536    ;LENG   )
00017'003000            1536    ;IBLOC  )
00020'000400            256     ;KEY    )
                ;
00021'177770    COUNT:  -8      ;MINUS NO. OF ARRAYS
      000010            .RDX    8
00022'001000    STEP:   1000
00023'100600    HIGH:   77600+1000      ;ALLOWS 200 WDS FOR LDR
00024'000303'   IPXR:   IPX
00025'000304'   IPYR:   IPY
00026'000000    IBLOC:  0
                ;
00027'034761    TRANS:  LDA     3,TBL
00030'030771            LDA     2,COUNT
00031'126400            SUB     1,1
                ;TO FIND TOTAL COMMON BLOCK SIZE
00032'021400    SUM:    LDA     0,0,3
00033'107000            ADD     0,1
00034'175400            INC     3,3
```

```
00035'151404            INC     2,2,SZR
00036'000774            JMP     SUM
                ;COMMON SIZE IN AC1
                ;NOW SIZE CORE
00037'020763            LDA     0,STEP
00040'034763            LDA     3,HIGH
00041'116400            SUB     0,3
00042'055777            STA     3,-1,3
00043'031777            LDA     2,-1,3
00044'156414            SUB#    2,3,SZR
00045'000774            JMP     .-4
00046'050000-           STA     2,.MEM
                ;HIGHEST USEABLE MEMORY IS IN AC2
00047'132400            SUB     1,2      ;LOWEST LOC. OF COMMON
00050'050733            STA     2,KEY
                ;COMPUTE LOCATIONS OF INDIVIDUAL ARRAYS
00051'024747            LDA     1,TBL+10
00052'133000            ADD     1,2
00053'050753            STA     2,IBLOC
00054'024743            LDA     1,TBL+7
00055'133000            ADD     1,2
00056'050726            STA     2,LENG
00057'024737            LDA     1,TBL+6
00060'133000            ADD     1,2
00061'050717            STA     2,AREA
00062'024733            LDA     1,TBL+5
00063'133000            ADD     1,2
00064'050715            STA     2,ICX
00065'024727            LDA     1,TBL+4
00066'133000            ADD     1,2
00067'050713            STA     2,ICY
00070'024723            LDA     1,TBL+3
00071'133000            ADD     1,2
00072'052732            STA     2,@IPXR
00073'024717            LDA     1,TBL+2
00074'133000            ADD     1,2
00075'052730            STA     2,@IPYR
00076'030706            LDA     2,LENG
00077'021377            LDA     0,-1,2
00100'040012-           STA     0,.NUM   ;NUMBER OF BLOCKS
00101'101005            MOV     0,0,SNR
00102'006006$           JSR     @.OVL    ;EXIT....NO BLOCKS
00103'022702            LDA     0,@NMAX  ;SET UP START OF DATA AREA
00104'040001-           STA     0,.M1
00105'024701            LDA     1,F400
00106'123000            ADD     1,0
00107'040002-           STA     0,.M2
00110'102400            SUB     0,0      ;INITIALIZE COUNTERS
00111'040566            STA     0,NB
00112'040566            STA     0,NP
00113'034001-           LDA     3,.M1    ;INITIALIZE POINTERS
00114'054566            STA     3,PPNT
00115'030002-           LDA     2,.M2
00116'050563            STA     2,BPNT
00117'051400            STA     2,0,3    ;FIRST BLOCK POINTER INSTALLED
                ;
00120'034660    BACK:   LDA     3,AREA
00121'024556            LDA     1,NB
00122'137000            ADD     1,3      ;GET AREA, BLOCK NB
00123'021400            LDA     0,0,3
```

```
00124'101004         MOV      0,0,SER
00125'101112         MOVL#    0,0,SEC
00126'002661         JMP      @NEXTR   ;NEGATIVE, OR ZERO, AREA
                ;
00127'041014         STA      0,14,2   ;STORE AREA
00130'102400         SUB      0,0      ;INITIALIZE THE FOLLOWING:
00131'040562         STA      0,MAX
00132'041002         STA      0,2,2    ;LOW X
00133'041004         STA      0,4,2    ;LOW Y
00134'041011         STA      0,11,2   ;(SIN)
00135'041005         STA      0,5,2    ;X-VEL
00136'041006         STA      0,6,2    ;ALPHA-DOT
00137'041012         STA      0,12,2   ;LOW ALPHA
00140'041007         STA      0,7,2    ;XFSUM
00141'041015         STA      0,15,2   ;Y-VEL
00142'041016         STA      0,16,2   ;YFSUM
00143'041017         STA      0,17,2   ;MSUM
00144'041020         STA      0,20,2   ;DELTA-X
00145'041021         STA      0,21,2   ;DELTA-Y
00146'041022         STA      0,22,2   ;DELTA-ALPHA
00147'041023         STA      0,23,2   ;X LOAD
00150'041024         STA      0,24,2   ;Y LOED
00151'100000         COM      0,0
00152'041010         STA      0,10,2   ;(COS) = NEAREST THING TO 1
                ;
00153'034626         LDA      3,ICX
00154'137000         ADD      1,3
00155'021400         LDA      0,0,3    ;GET ICX(NB)
00156'041001         STA      0,1,2    ;PUT IN NEW BLOCK LIST
00157'040537         STA      0,IX     ;TEMP STORE FOR LATER USE
00160'034622         LDA      3,ICY
00161'137000         ADD      1,3
00162'021400         LDA      0,0,3    ;GET ICY(NB)
00163'041003         STA      0,3,2    ;PUT IT AWAY
00164'040531         STA      0,IY     ;AS WITH IX
00165'034616         LDA      3,KEY
00166'137000         ADD      1,3
00167'021400         LDA      0,0,3    ;KEY(NB)
00170'025401         LDA      1,1,3    ;KEY(NB+1)
00171'106400         SUB      0,1
00172'045000         STA      1,0,2    ;NUMBER OF POINTS THIS BLOCK
00173'024013-        LDA      1,.BSIZ
00174'133000         ADD      1,2
00175'126520         SUBZL    1,1
00176'122400         SUB      1,0      ;KEY(NB)-1
00177'034605         LDA      3,LENG   ;POINTER TO LENGTH ARRAY
00200'117000         ADD      0,3
00201'054506         STA      3,FANG
00202'054506         STA      3,FENG
00203'034623         LDA      3,IBLOC
00204'117000         ADD      0,3
00205'054504         STA      3,FING
00206'054504         STA      3,FONG   ;2ND. COPY FOR LONG BLOCK
                ;
00207'021400  LOOP:  LDA      0,0,3    ;POINT NUMBER
00210'122400         SUB      1,0      ;P. NUM -1
00211'034472         LDA      3,IPX
00212'117000         ADD      0,3      ;POINTER TO X CO-ORD IN IPX
00213'025400         LDA      1,0,3    ;X CO-ORD IN AC1
00214'034470         LDA      3,IPY
```

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```
00215'117000            ADD     0,3        ;POINTER TO Y CO-ORD IN AC3
00216'020500            LDA     0,IX       ;GET XC BACK
00217'122400            SUB     1,0        ;XC-XP (RELATIVE X, XR)
00220'100400            NEG     0,0
00221'040465            STA     0,TEMP
00222'024463            LDA     1,ONE27    ;127
00223'101112            MOVL#   0,0,SZC
00224'100400            NEG     0,0        ;ABS(XR)
00225'106512            SUBL#   0,1,SZC    ;IS ABS(XR)>127 ?
00226'000472            JMP     FWORD      ;YES, TREAT AS LONG BLOCK
00227'024464            LDA     1,MAX      ;IS IS SHORTEST?
00230'106512            SUBL#   0,1,SZC
00231'0  462            STA     0,MAX
00232'0  454            LDA     0,TEMP     ;GET AC0 WITH CORRECT SIGN
00233'024005S           LDA     1,.MSKR
00234'123700            ANDS    1,0        ;MASK OFF LEFT BYTE, AND SWAP
00235'025400            LDA     1,0,3      ;Y CO-ORD IN AC1
00236'115000            MOV     0,3        ;RETAIN XR IN LEFT BYTE OF AC3
00237'020456            LDA     0,IY       ;GET YC BACK
00240'122400            SUB     1,0        ;YC-YP (RELATIVE Y, YR)
00241'100400            NEG     0,0        ;TO CORRECT A BLUNDER !
00242'040444            STA     0,TEMP
00243'024442            LDA     1,ONE27    ;DO AS WITH X...
00244'101112            MOVL#   0,0,SZC
00245'100400            NEG     0,0
00246'106512            SUBL#   0,1,SZC
00247'000451            JMP     FWORD      ;MUST BE LONG BLOCK
00250'024443            LDA     1,MAX
00251'106512            SUBL#   0,1,SZC
00252'040441            STA     0,MAX
00253'020433            LDA     0,TEMP
00254'024005S           LDA     1,.MSKR
00255'123400            AND     1,0        ;MASK OFF LEFT BYTE..
00256'163000            ADD     3,0        ;...AND ADD IN XR
00257'041000            STA     0,0,2      ;STORE FULL WORD IN LIST
00260'034427            LDA     3,FANG
00261'021400            LDA     0,0,3      ;GET LENGTH OF SIDE NP
00262'041001            STA     0,1,2      ;STORE LENGTH IN 2ND WORD
00263'010415            ISZ     NP
00264'020414            LDA     0,NP
00265'026414            LDA     1,@BPNT    ;GET MAX POINTS
00266'151400            INC     2,2        ;BUMP POINT POINTER
00267'151400            INC     2,2
00270'122513            SUBL#   1,0,SNC    ;IS NP > MAXP ?
00271'000507            JMP     OUT        ;YES, END OF POINT LOOP
00272'010417            ISZ     FING       ;NO, CARRY ON
00273'010414            ISZ     FANG
00274'034415            LDA     3,FING     ;POINTER TO IBLOC ARRAY
00275'126520            SUBZL   1,1
00276'000711            JMP     LOOP       ;ROUND AGAIN WE GO
                  ;
00277'000000      NB:      0
00300'000000      NP:      0
00301'000000      BPNT:    0
00302'000000      PPNT:    0
00303'035600      IPX:     35600               ;FORTRAN POINT ARRAYS
00304'036600      IPY:     36600
00305'000177      ONE27:   177
00306'000000      TEMP:    0
00307'000000      FANG:    0
```

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---
00310'000000  FENG:   0
00311'000000  FING:   0
00312'000000  FONG:   0
00313'000000  MAX:    0
00314'000000  SAVE:   0
00315'000000  IY:     0
00316'000000  IX:     0
00317'020000  LBIT:   020000  ;LONG BLOCK FLAG
              ;
              ;THIS SECTION USED WHEN LONG BLOCKS ARE FOUND
00320'102400  FWORD:  SUB     0,0
00321'040757          STA     0,NP     ;RESTORE POINT COUNTER
00322'024757          LDA     1,BPNT
00323'030013-         LDA     2,.BSIZ  ;START OF POINT DATA
00324'133000          ADD     1,2      ;RESTORE POINT POINTER
00325'034765  LOOPL:  LDA     3,FONG   ;POINTER TO IBLOC ARRAY START
00326'126520          SUBZL   1,1
00327'021400          LDA     0,0,3    ;POINT NUMBER
00330'122400          SUB     1,0      ;PNUM-1
00331'034752          LDA     3,IPX
00332'117000          ADD     0,3      ;POINTER TO X CO-ORD IN AC3
00333'025400          LDA     1,0,3    ;X CO-ORD IN AC1
00334'034750          LDA     3,IPY
00335'117000          ADD     0,3      ;POINTER TO Y CO-ORD IN AC3
00336'020760          LDA     0,IX     ;GET XC BACK
00337'106400          SUB     0,1      ;XP-XC (RELATIVE X, XR)
00340'045000          STA     1,0,2    ;STORE XR IN LIST
00341'125112          MOVL#   1,1,SZC  ;TO RECORD MAX DIMENSION
00342'124400          NEG     1,1
00343'020750          LDA     0,MAX
00344'122512          SUBL#   1,0,SZC
00345'044746          STA     1,MAX
00346'151400          INC     2,2      ;BUMP   POINT POINTER
00347'025400          LDA     1,0,3    ;Y CO-ORD
00350'020745          LDA     0,IY     ;YC BACK
00351'106400          SUB     0,1      ;YP-YC (RELATIVE Y, YR)
00352'045000          STA     1,0,2    ;PUT IT AWAY
00353'125112          MOVL#   1,1,SZC
00354'124400          NEG     1,1
00355'020736          LDA     0,MAX
00356'122512          SUBL#   1,0,SZC
00357'044734          STA     1,MAX
00360'151400          INC     2,2      ;BUMP POINT POINTER
00361'034727          LDA     3,FENG
00362'021400          LDA     0,0,3    ;LENGTH SIDE NP
00363'041000          STA     0,0,2
00364'151400          INC     2,2
00365'010713          ISZ     NP
00366'020712          LDA     0,NP
00367'026712          LDA     1,@BPNT
00370'122513          SUBL#   1,0,SNC
00371'000404          JMP     OUTR     ;POINT LIST DONE
00372'010720          ISZ     FONG
00373'010715          ISZ     FENG
00374'000731          JMP     LOOPL
00375'020722  OUTR:   LDA     0,LBIT
00376'107000          ADD     0,1
00377'046702          STA     1,@BPNT  ;ADD IN LONG BLOCK FLAG
              ;
00400'102400  OUT:    SUB     0,0
```

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---
00401'040677            STA     0,NP      ;RESET POINT COUNTER
00402'034677            LDA     3,BPNT
00403'050676            STA     2,BPNT
00404'010676            ISZ     PPNT
00405'052675            STA     2,@PPNT
00406'102400            SUB     0,0
00407'024704            LDA     1,MAX
00410'030005S           LDA     2,.MSKR ;>256 NOT ALLOWED
00411'132512            SUBL#   1,2,SZC
00412'145000            MOV     2,1
00413'131000            MOV     1,2
00414'073301            MUL
00415'045413            STA     1,13,3   ;D*D (MAX) FOR M. OF I.
00416'030663            LDA     2,BPNT
00417'010660  NEXT:     ISZ     NB
00420'024012-           LDA     1,.NUM
00421'020656            LDA     0,NB
00422'122512            SUBL#   1,0,SZC ;IS NB>=NBLOC ?
00423'002435            JMP     @BACKR  ;NO, KEEP GOING...
00424'102400            SUB     0,0
00425'042655            STA     0,@PPNT ;PUT ZERO ADDRESS IN LOCATOR LIS
00426'050003-           STA     2,.M3    ;NEXT FREE MEMORY
              ;THE NEXT PART CLASSIFIES ALL POINTS
              ;IN COARSE BOXES.
00427'024432            LDA     1,BOXSZ
00430'134400            NEG     1,3
00431'147000            ADD     2,1      ;LINK ARRAY START
00432'044004-           STA     1,.M4
00433'044432            STA     1,FREE
00434'102000            ADC     0,0
              ;NOTE: LINK = 17777 MEANS END OF LIST.
00435'041000  PIG:      STA     0,0,2    ;SET ALL LINKS TO 17777
00436'151400            INC     2,2      ; INITIALLY
00437'175404            INC     3,3,SZR
00440'000775            JMP     PIG
00441'102400            SUB     0,0
00442'040420            STA     0,NBA    ;BLOCK NUMBER
00443'034001-           LDA     3,.M1
00444'054422            STA     3,PPNTA
00445'032421  AROUN:    LDA     2,@PPNTA
00446'151005            MOV     2,2,SNR ;END OF LIST?
00447'000465            JMP     DONE     ;YES
00450'021000            LDA     0,0,2    ;FIRST BLOCK WORD
00451'024420            LDA     1,MSKR
00452'123400            AND     1,0      ;GET POINT COUNT ONLY
00453'040414            STA     0,PCNT   ; POINT COUNT
00454'126400            SUB     1,1
00455'044406            STA     1,NPA    ;RESET POINT COUNTER
00456'006001S           JSR     @.PON1   ;GET CO-ORDS OF FIRST POINT
00457'000416            JMP     PLACE
00460'000120' BACKR:    BACK
00461'000320  BOXSZ:    320     ;BOX ARRAY SIZE (20*15 OCTAL)
00462'000000  NBA:      0
00463'000000  NPA:      0
00464'000400  PRODZ:    400     ;PROD LOCATOR SIZE
00465'000000  FREE:     0
00466'000000  PPNTA:    0
00467'000000  PCNT:     0
00470'000100  C100:     100
00471'000377  MSKR:     000377
```

```
00472'000000  NY:     0
00473'024770  COW:    LDA     1,NPA
00474'006002$         JSR     @.PON2  ;QUICK ENTRY
00475'044775  PLACE:  STA     1,NY    ;NOW PUT NX IN AC1
00476'105000          MOV     0,1     ;NOW COMPUTE WHICH BOX
00477'034003-         LDA     3,.M3   ;THE POINT NX, NY SHOULD BE
00500'030770          LDA     2,C100  ;ASSOCIATED WITH, AND PLANT A
00501'102400          SUB     0,0     ;LINK TO IT IN THE BOX ARRAY.
00502'073101          DIV             ; INPUT: NX IN AC1
00503'137000          ADD     1,3     ;AC3=AC3+NX/100
00504'102400          SUB     0,0
00505'024765          LDA     1,NY
00506'073101          DIV
00507'127120          ADDZL   1,1
00510'127120          ADDZL   1,1
00511'137000          ADD     1,3     ;AC3=AC3+(NY/100)*20
00512'021400          LDA     0,0,3   ;FIRST LINK (MAY BE 0)
00513'030752          LDA     2,FREE  ;FREE SPACE POINTER
00514'041001          STA     0,1,2   ;PUT OLD LINK IN 2ND WORD
00515'051400          STA     2,0,3   ;PUT NEW LINK IN BOX ARRAY
00516'024744          LDA     1,NBA
00517'020744          LDA     0,NPA
00520'101300          MOVS    0,0
00521'123000          ADD     1,0     ;COMPOSITE (NPA:NBA)
00522'041000          STA     0,0,2   ;PUT IN 1ST WORD
00523'151400          INC     2,2
00524'151400          INC     2,2
00525'050740          STA     2,FREE  ;UPDATE FREE POINTER
00526'010735          ISZ     NPA
00527'014740          DSZ     PCNT    ;DONE IF PCNT=0
00530'000743          JMP     COW
00531'010735          ISZ     PPNTA
00532'010730          ISZ     NBA
00533'000712          JMP     AROUN
00534'030731  DONE:   LDA     2,FREE
00535'050005-         STA     2,.M5   ;NEXT FREE LOCATION
              ;NOW PREPARE FOR PROD LIST
00536'024726          LDA     1,PRODZ
00537'134400          NEG     1,3
00540'147000          ADD     2,1     ;PROD LIST START
00541'044006-         STA     1,.M6   ;FIXED POINTER
00542'044007-         STA     1,.M7   ;MOVING POINTER
00543'102000          ADC     0,0
00544'040010-         STA     0,.EMPT ;NOTHIMG IN EMPTY LIST
00545'041000  ITR:    STA     0,0,2   ;SET ALL LINKS TO -1
00546'151400          INC     2,2
00547'175404          INC     3,3,SZR
00550'000775          JMP     ITR
00551'006010$         JSR     @.TPRN
00552'006004$         JSR     @.DISS  ;DISPLAY ALL BLOCKS
00553'006007$         JSR     @.MESS
00554'000561'         TEXT
      000012          .RDX    10
00555'177076         -450
00556'000017          15
      000010          .RDX    8
00557'002401          JMP     @CNTRL
00560'177777  CNTRL:  CONTR
00561'050040  TEXT:   .TXT  * P
00562'040510  HA
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---
 00563'042523  SE
 00564'052040   T
 00565'051110  HR
 00566'042505  EE
 00567'000000  *
      000027'           .END    TRANS
```

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```
                               .TITL   TEK
                          ;TO PLOT A POINT ON THE TEKTRONIX SCREEN:
                          ;
                          ;        JSR @.PLTS
                          ;  (PUT 0 HERE FOR BEAM OFF,
                          ;        1 FOR BEAM ON,
                          ;        -1 FOR POINT PLOT)
                          ; INPUT: AC0 = X CO-ORDINATE
                          ;         AC1 = Y CO-ORDINATE
                          ;
                          ;TO GET CURSOR CO-ORDINATES AND CHARACTER:
                          ;
                          ;        JSR @.CURS
                          ;        CHAR
                          ;        X
                          ;        Y
                          ;WHERE:
                          ;        CHAR=ADDRESS OF WORD CONTAINING
                          ;                KEY CHARACTER,
                          ;        X    =ADDRESS OF WORD WITH X CO-ORD,
                          ;        Y    =   "    "    "    "   Y   "
                          ;
                                   .ENT    .PLTS,.CURS
                                   .ZREL
00000-000017' .PLTS:      TPLOT
00001-000150' .CURS:      CURSIS
                                   .NREL
00000'040416  CHIN:       STA      0,CCAC0 ;SAVE AC0
00001'063610              SKPDN    TTI      ;SKP IF CHAR READY
00002'000777              JMP      .-1
00003'060510              DIAS     0,TTI   ;READ CHAR
00004'043400              STA      0,@0,3  ;STORE CHAR
00005'020411              LDA      0,CCAC0 ;RESTORE ACO
00006'001401              JMP      1,3     ;RETURN
00007'040407  CHOUT:      STA      0,CCAC0 ;SAVE AC0
00010'063511              SKPBZ    TTO      ;SKIP IF NOT BUSY
00011'000777              JMP      .-1
00012'023400              LDA      0,@0,3  ;GET CHARACTER
00013'061111              DOAS     0,TTO   ;SHIP CHARACTER
00014'020402              LDA      0,CCAC0 ;RESTORE AC0
00015'001401              JMP       1,3
00016'000000  CCAC0:      0                 ;TEMP FOR AC0
00017'040525  TPLOT:      STA      0,TPTX   ;X CO-ORD
00020'044525              STA      1,TPTY   ;Y CO-ORD
00021'021400              LDA      0,0,3   ;MODE FROM CALL+1
00022'040524              STA      0,TPMOD
00023'054520              STA      3,TPTADD;SAVE CALL ADDRESS
00024'101015              MOV#     0,0,SNR ;SKP IF NEQ 0
00025'000405              JMP      TPTDV    ;= 0  INITIALIZE AND DARK VECTOR
00026'101113              MOVL#    0,0,SNC ;SKIP IF < 0
00027'000405              JMP      TPTNRM   ;NORMAL BRIGHT VECTOR
00030'006511              JSR      @CHOUZ   ;SET TO ALPHA
00031'000130'             US
00032'006507  TPTDV:      JSR      @CHOUZ   ;DARK VECTOR
00033'000127'             GS
00034'020511  TPTNRM:     LDA      0,TPTY   ;GET Y
00035'101112              MOVL#    0,0,SZC ;SKP IF +
00036'102400              SUB      0,0     ;MAKE 0
00037'034477              LDA      3,D780   ;UPPER Y BOUND
00040'162513              SUBL#    3,0,SNC ;SKP IF ON SCREEN
```

```
00041'161000            MOV    3,0       ;SET TO EDGE
00042'040503            STA    0,TPTY    ;SAVE GOOD Y
00043'101120            MOVZL  0,0       ;USE UPPER 5 BITS
00044'101120            MOVZL  0,0
00045'101120            MOVZL  0,0
00046'101300            MOVS   0,0       ;AND SWAP HALVES
00047'034463            LDA    3,B040    ;HI Y TAG
00050'163000            ADD    3,0       ;PUT IN CHAR
00051'040476            STA    0,TPTTMP;USE A TEMP
00052'006467            JSR    @CHOUZ    ;SHIP HI Y 5
00053'000147'           TPTTMP
00054'020471            LDA    0,TPTY    ;GET Y
00055'034453            LDA    3,B037    ;MASK
00056'163400            AND    3,0       ;LEAVE LOW Y 5
00057'034455            LDA    3,B140    ;LOW Y TAG
00060'163000            ADD    3,0       ;SET IN CHAR
00061'040466            STA    0,TPTTMP
00062'006457            JSR    @CHOUZ    ;SHIP LOW Y
00063'000147'           TPTTMP
00064'020460            LDA    0,TPTX    ;GET X VALUE
00065'101112            MOVL#  0,0,SZC
00066'102400            SUB    0,0
00067'034450            LDA    3,D1023
00070'162513            SUBL#  3,0,SNC
00071'161000            MOV    3,0
00072'040452            STA    0,TPTX
00073'101120            MOVZL  0,0       ;AND DO LIKE Y
00074'101120            MOVZL  0,0
00075'101120            MOVZL  0,0
00076'101300            MOVS   0,0       ;HI X 5
00077'034433            LDA    3,B040    ;HI X TAG
00100'163000            ADD    3,0       ;ADD IN TAG
00101'040446            STA    0,TPTTMP
00102'006437            JSR    @CHOUZ    ;SHIP HI X 5
00103'000147'           TPTTMP
00104'020440            LDA    0,TPTX    ;GET X
00105'034423            LDA    3,B037    ;GOODIE MASK
00106'163400            AND    3,0       ;LEAVE LOW X 5
00107'034424            LDA    3,B100    ;LOW X TAG
00110'163000            ADD    3,0       ;PUT IN TAG
00111'040436            STA    0,TPTTMP
00112'006427            JSR    @CHOUZ
00113'000147'           TPTTMP
00114'020432            LDA    0,TPMOD
00115'101113            MOVL#  0,0,SNC
00116'000404            JMP    TPTEXT
00117'102400            SUB    0,0
00120'040426            STA    0,TPMOD
00121'000713            JMP    TPTNRM
00122'020420    TPTEXT: LDA    0,TPTAC0;RESTORE AC0
00123'034420            LDA    3,TPTADD;CALL ADDRESS
00124'001401            JMP    1,3       ;EXIT AT CALL+1
00125'000032    SUBQQ:  032
00126'000033    ESC:    033
00127'000035    GS:     035
00130'000037    US:     037
00131'000020    B020:   020
      000130'   B037=US
00132'000040    B040:   040
00133'000100    B100:   100
```

```
00134'000140  B140:   140
00135'000003  D003:   003
00136'001414  D780:   1414
00137'001777  D1023:  1777
00140'000000' CHINP:  CHIN
00141'000007' CHOUZ: CHOUT
00142'000000  TPTAC0: 0
00143'000000  TPTADD: 0
00144'000000  TPTX:   0
00145'000000  TPTY:   0
00146'000000  TPMOD:  0
00147'000000  TPTTMP: 0
00150'040772  CURSIS: STA     0,TPTAC0;SAVE AC0
00151'054772          STA     3,TPTADD;SAVE CALL ADDRESS
00152'006767          JSR     @CHOUZ  ;SET TO ALPHA
00153'000130'         US
00154'006765          JSR     @CHOUZ  ;TURN ON CURSER
00155'000126'         ESC
00156'006763          JSR     @CHOUZ
00157'000125'         SUBQQ
00160'006760          JSR     @CHINP  ;GET CHAR
00161'000144'         TPTX
00162'020753          LDA     0,D003  ;GET LOOP COUNTER
00163'040764          STA     0,TPTTMP
00164'020760          LDA     0,TPTX  ;GET CHAR
00165'000421          JMP     CURPS   ;STORE CHAR
00166'006752  CURLP:  JSR     @CHINP  ;GET HI COORD
00167'000144'         TPTX
00170'006750          JSR     @CHINP  ;GET LOW COORD
00171'000145'         TPTY
00172'034736          LDA     3,B037  ;MASK
00173'020752          LDA     0,TPTY  ;LOW COORD
00174'163400          AND     3,0     ;MASK OFF GARBAGE
00175'040750          STA     0,TPTY  ;SAVE FOR LATER
00176'020746          LDA     0,TPTX  ;HI COORD
00177'163400          AND     3,0     ;MASK OFF
00200'101300          MOVS    0,0     ;SWAP
00201'101220          MOVZR   0,0
00202'101220          MOVZR   0,0
00203'101220          MOVZR   0,0
00204'034741          LDA     3,TPTY  ;LOW COORD
00205'163000          ADD     3,0     ;ADD IN LOW COORD
00206'034735  CURPS:  LDA     3,TPTADD;CALL ADDRESS
00207'043400          STA     0,@0,3  ;STORE VALUE
00210'175400          INC     3,3     ;ADJUST ADDRESS
00211'054732          STA     3,TPTADD;SAVE UPDATED ADD
00212'014735          DSZ     TPTTMP  ;CHECK FOR DONE
00213'000753          JMP     CURLP   ;LOOP IF NOT
00214'020726          LDA     0,TPTAC0;RESTORE AC0
00215'001400          JMP     0,3     ;RETURN
                      .END
```

```
                   .TITL   PONT
            ;ROUTINE TO RETURN GLOBAL CO-ORDINATES
            ;OF POINT NP, BLOCK NB
            ;INPUT: AC1 = POINT # NP
            ;        AC2 = POINTER TO START
            ;                OF DATA, BLOCK NB.
            ;
            ;OUTPUT:AC0 = X CO-ORDINATE
            ;        AC1 = Y CO-ORDINATE
            ;        AC2 IS PRESERVED.
            ;
            ;ENTRIES:
            ;        JSR @.PON1 , FOR NORMAL ENTRY
            ;
            ;        JSR @.PON2 , IF PREVIOUS CALL WAS
            ;                     FOR THIS BLOCK (AC2
            ;                     NOT NEEDED).
            ;
                   .ENT    .PON1,.PON2
                   .EXTD   .BSIZ
                   .ZREL
00000-000000' .PON1:  PONT1
00001-000170' .PON2:  PONT2
                   .NREL
00000'054544  PONT1:  STA     3,SV3
00001'021000          LDA     0,0,2    ;1ST WORD
00002'034545          LDA     3,LBIT
00003'117400          AND     0,3      ;AC3=LONG BLOCK INDICATOR
00004'054555          STA     3,IND3
00005'040547          STA     0,SINF   ;SIN FLAG IN BIT 0
00006'101100          MOVL    0,0
00007'040546          STA     0,COSF   ;COS FLAG IN BIT 0
00010'021001          LDA     0,1,2    ;X CENTROID
00011'040537          STA     0,XC
00012'021003          LDA     0,3,2    ;Y CENTROID
00013'040536          STA     0,YC
00014'021011          LDA     0,11,2   ;SIN
00015'040535          STA     0,SIN
00016'021010          LDA     0,10,2   ;COS
00017'040534          STA     0,COS
00020'050523          STA     2,SV2    ;BLOCK NB, DATA START
00021'020001S ENTQ:   LDA     0,.BSIZ  ;START OF POINT DATA
00022'113000          ADD     0,2      ;POINTER TO START OF
00023'175004          MOV     3,3,SZR  ;POINT LIST
00024'000536          JMP     LONG     ;LONG BLOCK
00025'127000          ADD     1,1      ;NP*2 FOR SHORT BLOCK
00026'133000          ADD     1,2      ;(POINT NP)
00027'020516          LDA     0,MASKR  ;0000000011111111
00030'025000          LDA     1,0,2    ;(XR:YR)
00031'135300          MOVS    1,3      ;(YR:XR)
00032'117400          AND     0,3      ;RIGHT 8 BITS XR IN AC3
00033'107400          AND     0,1      ;  "    "   "   YR " AC1
00034'030512          LDA     2,C200   ;MASK TO DETECT NEGATIVE
00035'147414          AND#    2,1,SZR
00036'106000          ADC     0,1      ;MAKE PROPER NEGATIVE
00037'157414          AND#    2,3,SZR
00040'116000          ADC     0,3      ;(ALL 16 BITS OK)
00041'044515  DOG:    STA     1,YR     ;XR IN AC3, YR IN AC1
00042'030510          LDA     2,SIN
00043'102440          SUBO    0,0
```

```
00044'125112    MOVL#   1,1,SZC ;-VE YR?
00045'124440    NEGO    1,1     ;YES. ABS(YR). SET CARRY
00046'073301    MUL             ;YR*SIN IN AC0
00047'125112    MOVL#   1,1,SZC ;ROUNDED ARITHMETIC
00050'101400    INC     0,0
00051'101002    MOV     0,0,SZC ;RESTORE SIGN
00052'100400    NEG     0,0
00053'024501    LDA     1,SINF
00054'125102    MOVL    1,1,SZC
00055'100400    NEG     0,0     ;-VE SIN
00056'024472    LDA     1,XC
00057'106400    SUB     0,1     ;X=XC-YR*SIN
00060'044500    STA     1,X
00061'165000    MOV     3,1
00062'030471    LDA     2,COS
00063'102440    SUBO    0,0
00064'125112    MOVL#   1,1,SZC
00065'124440    NEGO    1,1     ;SET CARRY IF AC1<0
00066'073301    MUL             ;XR*COS IN AC0
00067'125112    MOVL#   1,1,SZC
00070'101400    INC     0,0
00071'101002    MOV     0,0,SZC
00072'100400    NEG     0,0
00073'024462    LDA     1,COSF
00074'125102    MOVL    1,1,SZC
00075'100400    NEG     0,0     ;-VE COS
00076'024462    LDA     1,X
00077'107000    ADD     0,1     ;X=X+XR*COS
00100'044460    STA     1,X     ;GLOBAL X CO-ORD
00101'165000    MOV     3,1     ;XR
00102'030450    LDA     2,SIN
00103'102440    SUBO    0,0
00104'125112    MOVL#   1,1,SZC
00105'124440    NEGO    1,1
00106'073301    MUL             ;XR*SIN
00107'125112    MOVL#   1,1,SZC
00110'101400    INC     0,0
00111'101002    MOV     0,0,SZC
00112'100400    NEG     0,0
00113'024441    LDA     1,SINF
00114'125102    MOVL    1,1,SZC
00115'100400    NEG     0,0
00116'024433    LDA     1,YC
00117'107000    ADD     0,1     ;YC=YC+XR*SIN
00120'044437    STA     1,Y
00121'024435    LDA     1,YR
00122'030431    LDA     2,COS
00123'102440    SUBO    0,0
00124'125112    MOVL#   1,1,SZC
00125'124440    NEGO    1,1
00126'073301    MUL
00127'125112    MOVL#   1,1,SZC
00130'101400    INC     0,0
00131'101002    MOV     0,0,SZC
00132'100400    NEG     0,0
00133'024422    LDA     1,COSF
00134'125102    MOVL    1,1,SZC
00135'100400    NEG     0,0
00136'024421    LDA     1,Y
00137'107000    ADD     0,1     ;Y=Y+YR*COS
```

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```
---
00140'020420          LDA     0,X      ;OUTPUT:        XC IN AC0
00141'030402          LDA     2,SV2    ;               YC IN AC1
00142'002402          JMP     @SV3     ;           AC2 RESTORED
00143'000000  SV2:    0
00144'000000  SV3:    0
00145'000377  MASKR:  377
00146'000200  C200:   200
00147'020000  LBIT:   20000
00150'000000  XC:     0
00151'000000  YC:     0
00152'000000  SIN:    0
00153'000000  COS:    0
00154'000000  SINF:   0
00155'000000  COSF:   0
00156'000000  YR:     0
00157'000000  Y:      0
00160'000000  X:      0
00161'000000  IND3:   0
00162'135120  LONG:   MOVZL   1,3      ;NP*3 FOR LONG BLOCK
00163'167000          ADD     3,1
00164'133000          ADD     1,2      ;POINTER TO POINT NP (XR)
00165'035000          LDA     3,0,2    ;XR IN AC3
00166'025001          LDA     1,1,2    ;YR IN AC1
00167'000652          JMP     DOG
              ;ENTRY POINT IF THIS BLOCK WAS ADDRESSED ON THE LAST
              ;CALL.
00170'054754  PONT2:  STA     3,SV3
00171'034770          LDA     3,IND3
00172'030751          LDA     2,SV2
00173'000626          JMP     ENT0
                      .END
```

```
                        .TITL   HITS
                        .ENT    .HITS
                ;
                ;TO SCAN ALL SIDES FOR HIT ON POINT (X,Y)
                ;
                ;        JSR @.HITS
                ;          X
                ;          Y
                ;     (NO-HIT RETURN)
                ;     (HIT RETURN WITH BLOCK POINTER
                ;      IN AC2,  EDGE # IN AC1 AND BLOCK # IN AC0)
                ;     (X,Y) WILL BE OVERWRITTEN WITH THE COORDS
                ;     OF THE CENTRE OF THE LINE THAT WAS HIT
                ;     AC3 WILL CONTAIN RE-ENTRY ADDRESS FOR CONTINUED
                ;     SCAN, WITH RETURN TO ORIGINAL CALLING ADDRESS.
                ;     IF RE-ENTRY IS MADE TO C(AC3)+1, AC3 WILL BE
                ;     TAKEN AS THE NEW CALLING ADDRESS. (GET IT?)
                ;
                        .EXTD   .M1,.M2,.M3,.M4,.M5,.M6,.M7,.MSKR
                        .EXTD   .PON1,.PON2,.PRN1,.EMPT,.PSIZ,.LENG
                        .EXTD   .IACC,.PLTS,.ALPH
                        .ZREL
00000-000000' .HITS:    HITS
                        .NREL
00000'054424  HITS:     STA     3,HIT3
00001'023400            LDA     @0,0,3
00002'040521            STA     0,X
00003'023401            LDA     @0,1,3
00004'040520            STA     0,Y
00005'034001S           LDA     3,.M1
00006'102400            SUB     0,0
00007'040416            STA     0,NBB
              ;BLOCK SCAN------------
00010'054416  BEGIN:    STA     3,HOLD
00011'031400            LDA     2,0,3
00012'151005            MOV     2,2,SNR
00013'000407            JMP     BAD        ;NO MORE BLOCKS. EXIT!
00014'024411            LDA     1,NBB
00015'004412            JSR     SING       ;GO TO SIDE-SCAN ROUTINE
00016'010407            ISZ     NBB
00017'034407            LDA     3,HOLD
00020'175400            INC     3,3
00021'000767            JMP     BEGIN
00022'034402  BAD:      LDA     3,HIT3
00023'001402            JMP     2,3        ;NO-HIT RETURN
00024'000000  HIT3:     0
00025'000000  NBB:      0
00026'000000  HOLD:     0
              ;
              ;INPUT: AC1 - BLOCK #
              ;       AC2 - POINTER TO START OF DATA, BLOCK NB
              ;
00027'054455  SING:     STA     3,SIN3
00030'044470            STA     1,NB
00031'021014            LDA     0,14,2
00032'101005            MOV     0,0,SNR
00033'002451            JMP     @SIN3      ;ZERO AREA. EXIT!
00034'021000            LDA     0,0,2      ;CONTROL WORD
00035'024010S           LDA     1,.MSKR
00036'107400            AND     0,1        ;NO. OF POINTS
```

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```
00037'044446           STA     1,NPNTS ;POINT COUNTER
00040'126400           SUB     1,1
00041'044460           STA     1,NP
00042'006016S          JSR     @.LENG  ;GET LENGTH L THIS SIDE
00043'040457           STA     0,L
00044'006011S          JSR     @.PON1  ;GET GLOBAL CO-ORDS
00045'040441           STA     0,X0
00046'044441           STA     1,Y0
00047'040444           STA     0,XA
00050'044444           STA     1,YA
00051'000417           JMP     DOWN
00052'006016S BACK:    JSR     @.LENG  ;GET LENGTH L
00053'040435           STA     0,L1    ;LENGTH L, SIDE NP
00054'006011S          JSR     @.PON1
00055'040434           STA     0,XB
00056'044434           STA     1,YB
00057'050423           STA     2,AC2
00060'004446           JSR     PUSH    ;SEARCH FOR CONTACTS
00061'030421           LDA     2,AC2
00062'020427           LDA     0,XB    ;NEW BECOMES OLD
00063'040430           STA     0,XA
00064'020426           LDA     0,YB
00065'040427           STA     0,YA
00066'020422           LDA     0,L1
00067'040433           STA     0,L
00070'010431  DOWN:    ISZ     NP
00071'024430           LDA     1,NP
00072'014413           DSZ     NPNTS   ;JUMP OUT IF DONE
00073'000757           JMP     BACK
00074'020412           LDA     0,X0    ;LAST LINE
00075'040414           STA     0,XB
00076'020411           LDA     0,Y0
00077'040413           STA     0,YB
00100'004426           JSR     PUSH    ;SEARCH FOR CONTACTS
00101'002403           JMP     @SIN3   ;EXIT
00102'000000  AC2:     0
00103'020000  LBIT:    20000
00104'000000  SIN3:    0
00105'000000  NPNTS:   0
00106'000000  X0:      0
00107'000000  Y0:      0
00110'000000  L1:      0
00111'000000  XB:      0
00112'000000  YB:      0
00113'000000  XA:      0
00114'000000  YA:      0
00115'000000  COS:     0
00116'000000  SIN:     0
00117'000000  COSF:    0
00120'000000  NB:      0
00121'000000  NP:      0
00122'000000  L:       0
00123'000000  X:       0
00124'000000  Y:       0
00125'000000  SINF:    0
00126'054541  PUSH:    STA     3,SVP3
              ;TO GET LOCAL COS AND SIN OF THIS EDGE
00127'020762           LDA     0,XB
00130'024763           LDA     1,XA
00131'122400           SUB     1,0     ;XB-XA
```

```
00132'040765         STA     0,COSF   ;COS SIGN FLAG
00133'101112         MOVL#   0,0,SZC ;-VE?
00134'100400         NEG     0,0      ;YES, GET ABS(XB-XA)
00135'030765         LDA     2,L      ;LENGTH OF EDGE
00136'126400         SUB     1,1
00137'142513         SUBL#   2,0,SNC ;XD>=L?
00140'124001         COM     1,1,SKP ;SET AC1 TO 1111...
00141'073101         DIV
00142'101112         MOVL#   0,0,SZC ;ROUND UP IF NECESSARY
00143'125400         INC     1,1
00144'044751         STA     1,COS
00145'020745         LDA     0,YB
00146'024746         LDA     1,YA
00147'122400         SUB     1,0      ;YB-YA
00150'040755         STA     0,SINF   ;SIN SIGN FLAG
00151'101112         MOVL#   0,0,SZC ;-VE?
00152'100400         NEG     0,0
00153'126400         SUB     1,1
00154'142513         SUBL#   2,0,SNC ;YD>=L?
00155'124001         COM     1,1,SKP ;YES
00156'073101         DIV
00157'101112         MOVL#   0,0,SZC
00160'125400         INC     1,1      ;ROUND UP
00161'044735         STA     1,SIN
                ;
                ;GET TRANSFORMED CO-ORDS OF X,Y
                ;COMPUTES: XT=XG*COS(A)+YG*SIN(A)
                ;          YT=YG*COS(A)-XG*SIN(A)
                ;
00162'020741         LDA     0,X      ;GET COORDS OF POINT
00163'024741         LDA     1,Y      ;UNDER CONSIDERATION
00164'034727         LDA     3,XA
00165'162400         SUB     3,0
00166'040477         STA     0,XG     ;REL. TO EDGE START
00167'034725         LDA     3,YA
00170'166400         SUB     3,1
00171'044475         STA     1,YG
00172'004477         JSR     YTGET    ;LOCAL, TRANSFORMED Y
                ;
00173'175112         MOVL#   3,3,SZC
00174'174400         NEG     3,3      ;ABS YT
00175'024017S        LDA     1,.IACC
00176'166423         SUBZ    3,1,SNC ;CHECK FOR NORMAL DIST.
00177'002470         JMP     @SVP3    ;NOT NEAR; EXIT!
                ;
00200'030716         LDA     2,SIN    ;NOW FOR XT
00201'024465         LDA     1,YG
00202'102440         SUBO    0,0
00203'125112         MOVL#   1,1,SZC ;SET CARRY IF NEG
00204'124440         NEGO    1,1      ;AND MAKE AC1 +VE
00205'073301         MUL
00206'125112         MOVL#   1,1,SZC
00207'101400         INC     0,0      ;ROUND UP
00210'101002         MOV     0,0,SZC ;CARRY?
00211'100400         NEG     0,0      ;RESTORE SIGN
00212'024713         LDA     1,SINF
00213'125102         MOVL    1,1,SZC ;SIGN OF SIN
00214'100400         NEG     0,0
00215'115000         MOV     0,3      ;SHUNT INTO AC3
00216'024447         LDA     1,XG
```

```
00217'030676          LDA     2,COS
00220'102440          SUBO    0,0
00221'125112          MOVL#   1,1,SZC
00222'124440          NEGO    1,1
00223'073301          MUL
00224'125112          MOVL#   1,1,SZC
00225'101400          INC     0,0
00226'101002          MOV     0,0,SZC
00227'100400          NEG     0,0
00230'024667          LDA     1,COSF
00231'125102          MOVL    1,1,SZC
00232'100400          NEG     0,0
00233'117000          ADD     0,3      ;ADD TO PREVIOUS RESULT
                ;LOCAL, TRANSFORMED X NOW IN AC3
                ;
00234'024666          LDA     1,L
00235'020017S         LDA     0,.IACC
00236'106400          SUB     0,1      ;L-5
00237'166433          SUBZ#   3,1,SNC
00240'002427          JMP     @SVP3    ;OFF THE END
00241'116433          SUBZ#   0,3,SNC
00242'002425          JMP     @SVP3    ;DITTO
                ;WE HAVE A HIT!
00243'036425          LDA     3,@HIT3R
00244'020647          LDA     0,XA
00245'024644          LDA     1,XB
00246'123220          ADDZR   1,0
00247'043400          STA     0,@0,3   ;STORE X MID-POINT
00250'020644          LDA     0,YA
00251'024641          LDA     1,YB
00252'123220          ADDZR   1,0
00253'043401          STA     0,@1,3   ;STORE Y MID-POINT
00254'024645          LDA     1,NP
00255'152520          SUBZL   2,2
00256'146400          SUB     2,1
00257'030623          LDA     2,AC2
00260'020640          LDA     0,NB
00261'005403          JSR     3,3      ;HIT EXIT
00262'002405          JMP     @SVP3    ;CARRY ON SCAN
00263'056405          STA     3,@HIT3R ;NEW RETURN ADDRESS
00264'002403          JMP     @SVP3    ;CARRY ON
00265'000000    XG:   0
00266'000000    YG:   0
00267'000000    SVP3: 0
00270'000024'   HIT3R: HIT3
                ;
                ;TO CALCULATE YT
                ; INPUT:  YG IN AC1
00271'054435    YTGET: STA    3,YTSAV
00272'030623          LDA     2,COS
00273'102440          SUBO    0,0
00274'125112          MOVL#   1,1,SZC
00275'124440          NEGO    1,1
00276'073301          MUL
00277'125112          MOVL#   1,1,SZC
00300'101400          INC     0,0
00301'101002          MOV     0,0,SZC
00302'100400          NEG     0,0
00303'024614          LDA     1,COSF
00304'125102          MOVL    1,1,SZC
```

```
00305'100400            NEG     0,0
00306'115000            MOV     0,3     ;PARTIAL SUM IN AC3
00307'024756            LDA     1,XG
00310'030606            LDA     2,SIN
00311'102440            SUBO    0,0
00312'125112            MOVL#   1,1,SEC
00313'124440            NEGO    1,1
00314'073301            MUL
00315'125112            MOVL#   1,1,SEC
00316'101400            INC     0,0
00317'101032            MOV     0,0,SEC
00320'100400            NEG     0,0
00321'024604            LDA     1,SINF
00322'125102            MOVL    1,1,SEC
00323'100400            NEG     0,0
00324'116400            SUB     0,3     ;SUBTRACT FROM PREVIOUS RESULT
00325'002401            JMP     @YTSAV
00326'000000    YTSAV:  0
                        .END
```

```
                        .TITL   TAPE
                        .ENT    .OVL,.CLNC,.RLNC,.WLNC
                        .ENT    .READ,.WRIT
                        .EXTD   .MEM,.M1,.M7
                        .ZREL
00000-000075' .OVL:     OVLAY
00001-000137' .CLNC:    CLINC
00002-000142' .RLNC:    RLINC
00003-000145' .WLNC:    WLINC
00004-000004' .READ:    RDP3
00005-000000' .WRIT:    WRTP3
                        .NREL
              ;--------------------------------------------
              ;THIS ROUTINE ALLOWS THE USER TO SAVE FILES
              ;WHILE IN P-3. IT FIRST WRITES (OR READS)
              ;PAGE ZERO ON THE LINC TAPE (UNIT #1,BLK#150)
              ;AND THEN WRITES (OR READS) THE LINKED FIELDS
              ;(BEGINNING AT BLK#151).
00000'054466  WRTP3:    STA     3,RSAVE
00001'176400            SUB     3,3
00002'054465            STA     3,FLAGF ;SET TO 0 FOR WRITE
00003'000404            JMP     BEG
00004'054462  RDP3:     STA     3,RSAVE
00005'176520            SUBZL   3,3
00006'054461            STA     3,FLAGF ;SET TO 1 FOR READ
00007'020527  BEG:      LDA     0,DRIVE
00010'062074            DOB     0,LINC
00011'020454            LDA     0,FBLK
00012'126520            SUBZL   1,1     ;ONE BLK FOR PAGE ZERO
00013'152400            SUB     2,2     ;START AT LCTN 0
00014'034453            LDA     3,FLAGF
00015'175004            MOV     3,3,SZR
00016'000402            JMP     READF
00017'000406            JMP     WRITF
00020'006002- READF:    JSR     @.RLNC
00021'125005            MOV     1,1,SNR
00022'000410            JMP     NXT1
00023'063077            HALT
00024'000763            JMP     BEG
00025'006003- WRITF:    JSR     @.WLNC
00026'125005            MOV     1,1,SNR
00027'000403            JMP     NXT1
00030'063077            HALT
00031'000756            JMP     BEG
00032'020504  NXT1:     LDA     0,DRIVE
00033'062074            DOB     0,LINC
00034'024003S           LDA     1,.M7   ;DETERMINE LENGTH OF
00035'030002S           LDA     2,.M1   ;LINKED FIELDS IN USE
00036'146400            SUB     2,1
00037'030425            LDA     2,C400
00040'102400            SUB     0,0
00041'073101            DIV
00042'020423            LDA     0,FBLK
00043'101400            INC     0,0     ;START AT FBLK+1
00044'125400            INC     1,1     ;ADD AN EXTRA BLOCK
00045'030002S           LDA     2,.M1   ;START @ LINKED LISTS
00046'034421            LDA     3,FLAGF
00047'175004            MOV     3,3,SZR
00050'000402            JMP     READG
00051'000406            JMP     WRITG
```

```
00052'006002- READG:  JSR     @.RLNC
00053'125005          MOV     1,1,SNR
00054'002412          JMP     @RSAVE
00055'063077          HALT
00056'000754          JMP     NXT1
00057'006003- WRITG:  JSR     @.WLNC
00060'125005          MOV     1,1,SNR
00061'002405          JMP     @RSAVE
00062'063077          HALT
00063'000747          JMP     NXT1
00064'000400  C400:   400
00065'000150  FBLK:   150
00066'000000  RSAVE:  0
00067'000000  FLAGF:  0
              ;-----------------------------------------
              ;THIS ROUTINE READS OVERLAY NUMBER 1
              ;FROM TAPE. IT STARTS BY FIRST TRANSFERING
              ;ITSELF TO A SAFE PLACE IN HIGH CORE.
00070'000000  NUB:    0                ;NO NEED TO TRANSFER P-3 R&W
00071'000002  TWO:    2                ;ROUTINES SO START AT NUB
00072'000003  THREE:  3
00073'000070' FIRST:  NUB
00074'000326' LAST:   C8
              ;
00075'020441  OVLAY:  LDA     0,DRIVE
00076'062074          DOB     0,LINC
00077'034001S         LDA     3,.MEM   ;HIGHEST MEMORY LCTN
00100'030773          LDA     2,FIRST
00101'020773          LDA     0,LAST
00102'142400          SUB     2,0      ;=NUMBER OF WORDS TO BE MOVED
00103'101400          INC     0,0
00104'116400          SUB     0,3      ;NEW ADDRESS
00105'100400          NEG     0,0
00106'025000  ROUND:  LDA     1,0,2
00107'045400          STA     1,0,3
00110'101405          INC     0,0,SNR
00111'000404          JMP     OUT
00112'151400          INC     2,2
00113'175400          INC     3,3
00114'000772          JMP     ROUND
00115'156400  OUT:    SUB     2,3      ;=DISTANCE MOVED
00116'030403          LDA     2,SHIFT
00117'157000          ADD     2,3
00120'001400          JMP     0,3      ; GO TO HI-CORE COPY
00121'000122' SHIFT:  .+1
00122'020412          LDA     0,BLK1
00123'024412          LDA     1,NBLK1
00124'152400          SUB     2,2
00125'004415          JSR     RLINC
00126'125005          MOV     1,1,SNR
00127'000377          JMP     377      ;FORTRAN START ADDRESS
00130'063077          HALT             ;LINC ERROR
00131'020405          LDA     0,DRIVE  ;TRY AGAIN (PRESS CONTINUE)
00132'062074          DOB     0,LINC
00133'000767          JMP     SHIFT+1
00134'000350  BLK1:   350
00135'000055  NBLK1:  55
00136'000001  DRIVE:  1
              ;NOW FOLLOWS THE STANDARD LINCTAPE
              ;UTILITIES...
```

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---
                     ;INPUT:   AC0 =FIRST BLOCK
                     ;         AC1 =NUMBER OF BLOCKS
                     ;         AC2 =FIRST CORE ADDRESS
                     ;
                     ;OUTPUT:  AC1 =ERROR CODE
                     ;
00137'054430  CLINC:  STA     3,SAC3
00140'152400          SUB     2,2
00141'000417          JMP     CHKZ
00142'054425  RLINC:  STA     3,SAC3
00143'034430          LDA     3,D2R
00144'000415          JMP     READZ
00145'054422  WLINC:  STA     3,SAC3
00146'034423          LDA     3,D1W
00147'054510          STA     3,D1XX
00150'044501          STA     1,D2XX
00151'050417          STA     2,SAC2
00152'004423          JSR     DO
00153'024476  RAW:    LDA     1,D2XX
00154'122400          SUB     1,0
00155'030413          LDA     2,SAC2
00156'151113          MOVL#   2,2,SNC
00157'150000          COM     2,2
00160'034473  CHKZ:   LDA     3,D2C
00161'054470  READZ:  STA     3,D2XX
00162'034410          LDA     3,D1RC
00163'054474          STA     3,D1XX
00164'004411          JSR     DO
00165'060274  EXIT:   NIOC    LINC
00166'002401          JMP     @SAC3
00167'000000  SAC3:   0
00170'000000  SAC2:   0
00171'021000  D1W:    LDA     0,0,2
00172'000750  D1RC:   JMP     READ-D1XX,1
00173'132512  D2R:    SUBL#   1,2,SZC
00174'000000  RETU:   0
00175'054777  DO:     STA     3,RETU
00176'075474          DIB     3,LINC
00177'175112          MOVL#   3,3,SZC
00200'000446          JMP     E4
00201'151113          MOVL#   2,2,SNC
00202'000410          JMP     FINDF
00203'150000          COM     2,2
00204'176400  FINDR:  SUB     3,3
00205'162000          ADC     3,0
00206'060374          NIOP    LINC
00207'004467          JSR     GETBL
00210'101401  FINDN:  INC     0,0,SKP
00211'000776          JMP     .-2
00212'060174  FINDF:  NIOS    LINC
00213'004463          JSR     GETBL
00214'000777          JMP     .-1
00215'175224          MOVZR   3,3,SZR
00216'000766          JMP     FINDR
00217'125005  FOUND:  MOV     1,1,SNR
00220'002754          JMP     @RETU
00221'166000          ADC     3,1
00222'040474          STA     0,TEMP1
00223'044474          STA     1,TEMP2
00224'024476          LDA     1,SIZE
```

```
---
00225'147000            ADD      2,1
00226'000431            JMP      DIXX
00227'063674  READ:     SKPDN    LINC
00230'000777            JMP      .-1
00231'063474            SKPBN    LINC
00232'000416            JMP      RDAT
00233'060474  RCHK:     DIA      0,LINC
00234'116405            SUB      0,3,SNR
00235'000434            JMP      SCHK
00236'024465  E1:       LDA      1,C1
00237'000403            JMP      .+3
00240'034462  E2:       LDA      3,SIZE
00241'024463            LDA      1,C2
00242'020454            LDA      0,TEMP1
00243'000722            JMP      EXIT
00244'024461  E3:       LDA      1,C4
00245'000720            JMP      EXIT
00246'024460  E4:       LDA      1,C8
00247'000716            JMP      EXIT
00250'060474  RDAT:     DIA      0,LINC
00251'132512  D2XX:     SUBL#    1,2,SZC
00252'041000            STA      0,0,2
00253'000402  D2C:      JMP      .+2
00254'061074  WDAT:     DOA      0,LINC
00255'117000  BLOOP:    ADD      0,3
00256'151400            INC      2,2
00257'021000  DIXX:     LDA      0,0,2
00260'063074            DOC      0,LINC
00261'063674            SKPDN    LINC
00262'000777            JMP      .-1
00263'063474            SKPBN    LINC
00264'000770            JMP      WDAT
00265'075074  WCHK:     DOA      3,LINC
00266'075474            DIB      3,LINC
00267'175004            MOV      3,3,SZR
00270'000756            JMP      E4
00271'132414  SCHK:     SUB#     1,2,SZR
00272'000746            JMP      E2
00273'020423  NEXT:     LDA      0,TEMP1
00274'024423            LDA      1,TEMP2
00275'000713            JMP      FINDN
00276'054420  GETBL:    STA      3,TEMP1
00277'034421            LDA      3,MLIM
00300'162432            SUBZ#    3,0,SZC
00301'000405            JMP      WAIT
00302'034417            LDA      3,PLIM
00303'162032            ADCZ#    3,0,SZC
00304'000740            JMP      E3
00305'074474            DIA      3,LINC
00306'063474  WAIT:     SKPBN    LINC
00307'000777            JMP      WAIT
00310'063774            SKPDZ    LINC
00311'000774            JMP      WAIT-1
00312'074474            DIA      3,LINC
00313'116543            SUBOL    0,3,SNC
00314'010402            ISZ      TEMP1
00315'002401            JMP      @TEMP1
00316'000000  TEMP1:    0
00317'000000  TEMP2:    0
00320'177770  MLIM:     177770
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```

```
00321'000620  PLIM:    620
00322'000400  SIZE:    400
00323'000001  C1:      1
00324'000002  C2:      2
00325'000004  C4:      4
00326'000010  C8:      10
                       .END
```

```
                  .TITL   UTIL
         ;SEVERAL UTILITY PROGRAMS
                  .ENT    .HITC,.IACC,.PRN1,.PAGE,.LENG,.SCAL
                  .ENT    .VFAC,.IPRN,.PRN2,.MESS,.ALPH,.TYP
                  .ENT    .AXIS,.GETT,.DBIN,.CHEK,.WORD,.DB0
                  .EXTD   .M1,.DISS,.LPAP,.MSKR,.PLTS
                  .ZREL
00000-000005  .IACC:  5
00001-000000' .HITC:  HITC
00002-000052' .PRN1:  PRN1
00003-000270' .PRN2:  PRN2
00004-000164' .IPRN:  TART
00005-000331' .MESS:  MESS
00006-000655' .WORD:  WORD
00007-000062' .ALPH:  ALPHA
00010-000067' .PAGE:  PAGE
00011-000101' .LENG:  LENG
00012-000126' .TYP:   TYPE
00013-000151' .SCAL:  SCAL
00014-000421' .AXIS:  AXIS
00015-000560' .GETT:  GET
00016-000572' .DBIN:  DBIN
00017-000570' .DB0:   DB0
00020-000640' .CHEK:  CHEK
00021-000003  .VFAC:  3
                      .NREL
              ;
              ;ROUTINE TO FIND WHICH BLOCK HAS CENTROID
              ;CORRESPONDING TO GIVEN X,Y CO-ORDINATE
              ;
              ;       JSR @.HITC
              ;       X     (ADDRESS OF INPUT X)
              ;       Y     (ADDRESS OF INPUT Y)
              ;    (RETURN HERE IF NO HIT)
              ;    (RETURN HERE WITH POINTER TO BLOCK
              ;       IN AC2 IF SUCCESSFUL, AND NB IN AC1)
              ;
00000'023400  HITC:   LDA     0,@0,3
00001'040445          STA     0,X
00002'023401          LDA     0,@1,3
00003'040444          STA     0,Y
00004'054444          STA     3,SVH3
00005'102400          SUB     0,0
00006'040443          STA     0,NB
00007'034001$         LDA     3,.M1
00010'031400  LOOP:   LDA     2,0,3
00011'151005          MOV     2,2,SNR
00012'000432          JMP     NOHIT   ;LAST BLOCK
00013'021014          LDA     0,14,2
00014'101005          MOV     0,0,SNR
00015'000424          JMP     NEXT    ;ZERO AREA
00016'021001          LDA     0,1,2   ;XC
00017'024427          LDA     1,X
00020'122400          SUB     1,0
00021'101112          MOVL#   0,0,SZC
00022'100400          NEG     0,0     ;ABS(XC-X)
00023'024000-         LDA     1,.IACC
00024'106512          SUBL#   0,1,SZC
00025'000414          JMP     NEXT    ;NOT THIS BLOCK
00026'021003          LDA     0,3,2   ;YC
```

```
00027'024420          LDA     1,Y
00030'122400          SUB     1,0
00031'101112          MOVL#   0,0,SZC
00032'100400          NEG     0,0      ;ABS(YC-Y)
00033'024000-         LDA     1,.IACC
00034'106512          SUBL#   0,1,SZC
00035'000404          JMP     NEXT
00036'034412          LDA     3,SVH3   ;MUST BE HIT
00037'024412          LDA     1,NB
00040'001403          JMP     3,3      ;GOOD EXIT
00041'175400  NEXT:   INC     3,3
00042'010407          ISZ     NB
00043'000745          JMP     LOOP
00044'034404  NOHIT:  LDA     3,SVH3
00045'001402          JMP     2,3      ;BAD EXIT
00046'000000  X:      0
00047'000000  Y:      0
00050'000000  SVH3:   0
00051'000000  NB:     0
              ;
              ;TO OUTPUT A SINGLE CHARACTER, WAITING
              ;UNTIL THE TTY IS FREE.
              ;
              ;       JSR @.PRN1
              ;       N     (N IS THE CHARACTER TO BE
              ;                PRINTED [NOT ADDRESS])
              ;             (ACCUMULATORS ARE SAVED)
              ;
00052'040407  PRN1:   STA     0,AC0SV
00053'021400          LDA     0,0,3
00054'063511  PRH:    SKPBZ   TTO
00055'000777          JMP     .-1
00056'061111          DOAS    0,TTO
00057'020402          LDA     0,AC0SV
00060'001401          JMP     1,3
00061'000000  AC0SV:  0
              ;
              ;TO SET TEKTRONIX TO ALPHA MODE
              ;       JSR @.ALPH
              ;
00062'054404  ALPHA:  STA     3,ASAV
00063'004767          JSR     PRN1
00064'000037          37
00065'002401          JMP     @ASAV
00066'000000  ASAV:   0
              ;
              ;TO ERASE SCREEN
              ;
              ;       JSR @.PAGE
              ;
00067'054410  PAGE:   STA     3,SVP3
00070'004762          JSR     PRN1
00071'000033          33
00072'004760          JSR     PRN1
00073'000014          14
00074'102400          SUB     0,0      ;SUPPRESS HARD-COPY
00075'040003S         STA     0,.LPAP ;LOAD PLOTTING
00076'002401          JMP     @SVP3
00077'000000  SVP3:   0
              ;
```

```
                  ;ROUTINE TO RETURN LENGTH, L OF SIDE NP
                  ;         JSR @.LENG
                  ;
                  ; INPUT:          AC1 - SIDE # (NP)
                  ;                 AC2 - POINTER TO BLOCK DATA
                  ; OUTPUT:         AC0 - LENGTH L
                  ;
        000025    START=25          ;POINT DATA STARTS AT 25RD WORD
        000026    SS=START+1
        000027    SL=START+2
    00100'007777  TMSK:     7777    ;TO REMOVE TYPE #
    00101'054776  LENG:     STA     3,SVP3
    00102'021000            LDA     0,0,2    ;CONTROL WORD
    00103'034420            LDA     3,LBIT
    00104'117414            AND#    0,3,SZR ;LONG BLOCK?
    00105'000407            JMP     LONG     ;YES
    00106'135120            MOVZL   1,3      ;NP*2
    00107'157000            ADD     2,3
    00110'021426            LDA     0,SS,3   ;GET L
    00111'034767            LDA     3,TMSK
    00112'163400            AND     3,0
    00113'002764            JMP     @SVP3    ;EXIT WITH L IN AC0
    00114'135120  LONG:     MOVZL   1,3
    00115'137000            ADD     1,3      ;NP*3
    00116'157000            ADD     2,3
    00117'021427            LDA     0,SL,3
    00120'034760            LDA     3,TMSK
    00121'163400            AND     3,0
    00122'002755            JMP     @SVP3    ;EXIT
    00123'020000  LBIT:     20000
                  ;
                  ;ROUTINE TO RETURN SURFACE TYPE #
                  ;FOR A GIVEN EDGE
                  ;         JSR @.TYP
                  ;INPUT:   AC2 = DATA POINTER FOR GIVEN BLOCK
                  ;         AC1 = EDGE # (NP)
                  ;OUTPUT:  AC0 = TYPE #
                  ;         AC1 AND AC2 ARE PRESERVED
                  ;
    00124'170000  LMSK:     170000  ;FOR MASKING OUT LENGTH PART
    00125'000000  TSAV:     0
    00126'054777  TYPE:     STA     3,TSAV
    00127'021000            LDA     0,0,2    ;CONTROL WD
    00130'034773            LDA     3,LBIT
    00131'117414            AND#    0,3,SZR
    00132'000405            JMP     LONG1
    00133'135120            MOVZL   1,3
       '34'157000           ADD     2,3
        35'021426           LDA     0,SS,3
        36'000405           JMP     NOSE
        37'135120  LONG1:   MOVZL   1,3
     0140'137000            ADD     1,3
    00141'157000            ADD     2,3
    00142'021427            LDA     0,SL,3
    00143'034761  NOSE:     LDA     3,LMSK
    00144'163700            ANDS    3,0
    00145'103120            ADDZL   0,0
    00146'103120            ADDZL   0,0
    00147'101300            MOVS    0,0
    00150'002755            JMP     @TSAV
```

```
                  ;
                  ;VECTOR SCALING ROUTINE
00151'030021- SCAL:    LDA     2,.VFAC
00152'102400           SUB     0,0
00153'044410           STA     1,AC1
00154'125112           MOVL#   1,1,SZC
00155'124400           NEG     1,1
00156'073101           DIV
00157'030404           LDA     2,AC1
00160'151112           MOVL#   2,2,SZC
00161'124400           NEG     1,1
00162'001400           JMP     0,3
00163'000000  AC1:     0
                  ;
                  ;ROUTINE TO PRINT A RIGHT-JUSTIFIED INTEGER
                  ;IN A GIVEN FIELD LENTH, WITH LEADING ZEROS
                  ;OR WITHOUT
                  ;
                  ;        JSR @.IPRN
                  ;    (-) N        (VALUE, NOT ADDRESS)
                  ;
                  ;        WHERE N IS FIELD LENGTH (ZEROS PRINTED
                  ;        IF NEGATIVE.
                  ;        THE NUMBER TO BE PRINTED IS IN AC0
                  ;
00164'031400  TART:    LDA     2,0,3
00165'101112           MOVL#   0,0,SZC
00166'100400           NEG     0,0
00167'175400           INC     3,3
00170'054524           STA     3,SAV3
00171'151112           MOVL#   2,2,SZC
00172'150401           NEG     2,2,SKP
00173'126401           SUB     1,1,SKP
00174'126520           SUBZL   1,1
00175'044520           STA     1,FLAG  ;STORE ZERO/BLANK FLAG
00176'050520           STA     2,FIELD ;FIELD LENGTH
00177'034475           LDA     3,TENS
00200'054517           STA     3,POINT
00201'034502           LDA     3,HOLD
00202'054516           STA     3,PPNT
00203'034507           LDA     3,JOLD
00204'054414           STA     3,MM
00205'152400           SUB     2,2
00206'036511  BIG:     LDA     3,@POINT
00207'010510           ISZ     POINT
00210'175005           MOV     3,3,SNR
00211'000416           JMP     END
00212'126400           SUB     1,1
00213'162422  SMALL:   SUBZ    3,0,SZC
00214'125401           INC     1,1,SKP
00215'163001           ADD     3,0,SKP
00216'000775           JMP     SMALL
00217'046501           STA     1,@PPNT
00220'125015  MM:      MOV#    1,1,SNR
00221'000404           JMP     FRED
00222'034471           LDA     3,JNEW
00223'054775           STA     3,MM
00224'151400           INC     2,2     ;COUNT NON-ZERO DIGITS
00225'010473  FRED:    ISZ     PPNT
00226'000760           JMP     BIG
```

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```
00227'034467  END:    LDA    3,FIELD
00230'151005          MOV    2,2,SNR
00231'151400          INC    2,2
00232'050467          STA    2,SAV2
00233'156423          SUBZ   2,3,SNC
00234'000427          JMP    ASTER   ;FIELD TOO SMALL
00235'170405          NEG    3,2,SNR
00236'000410          JMP    DIGIT   ;NO ZEROS
00237'024456          LDA    1,FLAG
00240'020463          LDA    0,ZERO
00241'125005          MOV    1,1,SNR
00242'020462          LDA    0,BLANK
00243'006003-         JSR    @.PRN2  ;SEND OUT LEADING
00244'151404          INC    2,2,SZR ;ZEROS OR BLANKS
00245'000776          JMP    .-2
00246'030443  DIGIT:  LDA    2,BOT
00247'024452          LDA    1,SAV2
00250'132400          SUB    1,2
00251'124405          NEG    1,1,SNR
00252'002442          JMP    @SAV3   ;NOTHING TO PRINT
00253'021000  LOOP1:  LDA    0,0,2
00254'034447          LDA    3,ZERO
00255'163000          ADD    3,0
00256'006003-         JSR    @.PRN2  ;SEND OUT DIGIT
00257'151400          INC    2,2
00260'125404          INC    1,1,SZR
00261'000772          JMP    LOOP1
00262'002432          JMP    @SAV3   ;EXIT
00263'020437  ASTER:  LDA    0,AST   ;SEND OUT ASTERISKS
00264'006003- NIT:    JSR    @.PRN2
00265'014431          DSZ    FIELD
00266'000776          JMP    NIT
00267'002425          JMP    @SAV3
              ;
              ;ROUTINE TO PRINT OUT SINGLE CHARACTER
              ;       JSR @.PRN2
              ;INPUT: CHARACTER IN AC0
              ;
00270'063511  PRN2:   SKPBZ   TTO
00271'000777          JMP     .-1
00272'061111          DOAS    0,TTO
00273'001400          JMP     0,3
              ;
      000012          .RDX    10
00274'000275' TENS:   .+1
00275'023420          10000
00276'001750          1000
00277'000144          100
00300'000012          10
00301'000001          1
00302'000000          0
00303'000304' HOLD:   .+1
      000005          .BLK    5
      000010          .RDX    8
00311'000311' BOT:    .
00312'125015  JOLD:   MOV#    1,1,SNR
00313'000404  JNEW:   JMP     .+4
00314'000000  SAV3:   0
00315'000000  FLAG:   0
00316'000000  FIELD:  0
```

```
---
00317'000000  POINT:  0
00320'000000  PPNT:   0
00321'000000  SAV2:   0
00322'000052  AST:    "*
00323'000060  ZERO:   "0
00324'000040  BLANK:  "
              ;
              ;TO PRINT MESSAGE ON SCREEN AT
              ;A SPECIFIC LOCATION
              ;
              ;         JSR @.MESS
              ;         TEXT     (ADDRESS OF TEXT)
              ;     (-) X        (X,Y LOCATION OF MESSAGE
              ;          Y        START [VALUES, NOT
              ;                   ADDRESSES]. NEGATIVE X DRAWS
              ;                   A LINE UNDER TEXT)
              ;
00325'000000  FLAG1:  0
00326'000000  MSAV:   0
00327'000000  BPNT:   0
00330'000000  COUNT:  0
00331'021400  MESS:   LDA     0,0,3
00332'101120          MOVZL   0,0     ;CREATE BYTE POINTER
00333'040774          STA     0,BPNT
00334'021401          LDA     0,1,3   ;X
00335'101112          MOVL#   0,0,SZC
00336'100401          NEG     0,0,SKP
00337'126401          SUB     1,1,SKP
00340'126520          SUBZL   1,1
00341'044764          STA     1,FLAG1
00342'025402          LDA     1,2,3   ;Y
00343'054763          STA     3,MSAV
00344'040451          STA     0,XSAV  ;REMEMBER X & Y FOR
00345'044451          STA     1,YSAV  ;LATER PLOTTING OF LINE
00346'006005S         JSR     @.PLTS  ;INITIALISE BEAM
00347'000000          0               ;BEAM OFF
00350'006007-         JSR     @.ALPH
00351'102400          SUB     0,0
00352'040756          STA     0,COUNT
              ;ROUTINE TO PICK BYTES UNTIL ZERO BYTE FOUND
00353'030754  PICK:   LDA     2,BPNT
00354'010753          ISZ     BPNT
00355'151220          MOVZR   2,2
00356'021000          LDA     0,0,2
00357'030004S         LDA     2,.MSKR
00360'101002          MOV     0,0,SZC
00361'101300          MOVS    0,0
00362'143405          AND     2,0,SNR
00363'000404          JMP     RET
00364'010744          ISZ     COUNT
00365'006003-         JSR     @.PRN2  ;SEND OUT CHARACTER
00366'000765          JMP     PICK
00367'020736  RET:    LDA     0,FLAG1
00370'101005          MOV     0,0,SNR
00371'000422          JMP     PAST
              ;TO PLOT LINE UNDER TEXT
00372'024424          LDA     1,YSAV
00373'020424          LDA     0,GAP
00374'106400          SUB     0,1
00375'044421          STA     1,YSAV
```

```
---
00376'020417            LDA     0,XSAV
00377'006005$           JSR     @.PLTS  ;FIRST END OF LINE
00400'000000            0
00401'102400            SUB     0,0
00402'024416            LDA     1,N14
00403'030725            LDA     2,COUNT
00404'073301            MUL
00405'020410            LDA     0,XSAV
00406'123000            ADD     1,0
00407'024407            LDA     1,YSAV
00410'006005$           JSR     @.PLTS  ;SECOND END
00411'000001            1
00412'006007-           JSR     @.ALPH
00413'034713  PAST:     LDA     3,MSAV
00414'001403            JMP     3,3     ;EXIT
00415'000000  XSAV:     0
00416'000000  YSAV:     0
00417'000003  GAP:      3       ;GAP BETWEEN TEXT AND LINE
00420'000016  N14:      16      ;WIDTH OF ONE LETTER
              ;
              ;TO DRAW A SCALE WITH 10 TICK MARKS,
              ;EITHER HORIZ. OR VERT., WITH THE
              ;MARKS ABOVE OR BELOW AXIS.
              ;
              ;         JSR @.AXIS
              ;         (-) L   (LENGTH)
              ;         (-) X   (STARTING X
              ;              Y     AND Y CO-ORD)
              ;         (ALL ARGUMENTS ARE VALUES, NOT
              ;            ADDRESSES)
              ;
              ;IF L HAS - SIGN, AXIS WILL BE PARALLEL
              ;TO Y AXIS; OTHERWISE PARALLEL TO X AXIS
              ;
              ;IF X HAS - SIGN, TICKS WILL BE BELOW
              ;AXIS, OTHERWISE ABOVE
              ;
00421'054521  AXIS:     STA     3,TTSAV
00422'021400            LDA     0,0,3
00423'101112            MOVL#   0,0,SZC
00424'100401            NEG     0,0,SKP
00425'126401            SUB     1,1,SKP
00426'126520            SUBZL   1,1
00427'044517            STA     1,FLOG  ;X/Y FLAG
00430'040505            STA     0,L
00431'021401            LDA     0,1,3
00432'101113            MOVL#   0,0,SNC
00433'000405            JMP     ABOVE
00434'100400            NEG     0,0
00435'024512            LDA     1,TICB
00436'044455            STA     1,REPL
00437'000403            JMP     GETY
00440'024510  ABOVE:    LDA     1,TICA
00441'044452            STA     1,REPL
00442'040474  GETY:     STA     0,XN
00443'025402            LDA     1,2,3
00444'044473            STA     1,YN
00445'030470            LDA     2,L
00446'151220            MOVZR   2,2
00447'151220            MOVZR   2,2
---
```

```
00450'151220          MOVER   2,2
00451'151220          MOVER   2,2
00452'151220          MOVER   2,2
00453'050465          STA     2,L1
00454'147000          ADD     2,1
00455'004474          JSR     PLOT
00456'000000          0
00457'020457          LDA     0,XN
00460'024457          LDA     1,YN
00461'004470          JSR     PLOT
00462'000001          1
00463'020453          LDA     0,XN
00464'024453          LDA     1,YN
00465'030450          LDA     2,L
00466'143000          ADD     2,0
00467'004462          JSR     PLOT
00470'000001          1
00471'020445          LDA     0,XN
00472'024445          LDA     1,YN
00473'030442          LDA     2,L
00474'143000          ADD     2,0
00475'030443          LDA     2,L1
00476'147000          ADD     2,1
00477'004452          JSR     PLOT
00500'000001          1
00501'102400          SUB     0,0
00502'024433          LDA     1,L
00503'030440          LDA     2,NINE
00504'050440          STA     2,TCNT
00505'151400          INC     2,2
00506'073101          DIV
00507'044436          STA     1,DIVIS
00510'020430          LDA     0,L1
00511'101220          MOVER   0,0
00512'024425          LDA     1,YN
00513'107000  REPL:   ADD     0,1       ;THIS WORD CAN BE CHANGED
00514'044425          STA     1,YN1
00515'024422  TEA:    LDA     1,YN      ;TO PLOT TICKS ON AXIS
00516'020420          LDA     0,XN
00517'030426          LDA     2,DIVIS
00520'143000          ADD     2,0
00521'040415          STA     0,XN
00522'004427          JSR     PLOT
00523'000000          0
00524'020412          LDA     0,XN
00525'024414          LDA     1,YN1
00526'004423          JSR     PLOT
00527'000001          1
00530'014414          DSZ     TCNT
00531'000764          JMP     TEA
00532'006007-         JSR     @.ALPH
00533'034407          LDA     3,TTSAV
00534'001403          JMP     3,3
00535'000000  L:      0
00536'000000  XN:     0
00537'000000  YN:     0
00540'000000  L1:     0
00541'000000  YN1:    0
00542'000000  TTSAV:  0
00543'000011  NINE:   11
```

```
---
00544'000000  TCNT:    0
00545'000000  DIVIS:   0
00546'000000  FLOG:    0
00547'106400  TICB:    SUB      0,1
00550'107000  TICA:    ADD      0,1
00551'030775  PLOT:    LDA      2,FLOG
00552'151005           MOV      2,2,SNR ;X OR Y AXIS?
00553'000404           JMP      JOE
00554'111000           MOV      0,2
00555'121000           MOV      1,0
00556'145000           MOV      2,1
00557'002005$ JOE:     JMP      @.PLTS
              ;
              ;TO GET A TTY CHARACTER
              ;        JSR      @.GETT
              ;OUTPUT: CHARACTER IN AC0
              ;
00560'063610  GET:     SKPDN    TTI
00561'000777           JMP      .-1
00562'060510           DIAS     0,TTI
00563'101300           MOVS     0,0
00564'101120           MOVZL    0,0
00565'101220           MOVZR    0,0
00566'101300           MOVS     0,0
00567'001400           JMP      0,3
              ;
              ;
              ;DECIMAL TO BINARY ROUTINE (ALMOST
              ;IDENTICAL TO DATA GENERAL'S)
              ;        JSR @.DBIN
              ;OUTPUT:          # IN AC1
              ;
00570'054443  DB0:     STA      3,DBSAV
00571'000403           JMP      DB1
00572'054441  DBIN:    STA      3,DBSAV
00573'006015-          JSR      @.GETT
00574'126400  DB1:     SUB      1,1       ;ENTRY WITH FIRST
00575'044437           STA      1,EC10    ;CHARACTER IN AC0
00576'044437           STA      1,EC11
00577'024437           LDA      1,EC20
00600'106405           SUB      0,1,SNR
00601'000405           JMP      EC96
00602'024435           LDA      1,EC21
00603'106404           SUB      0,1,SZR
00604'000404           JMP      EC98
00605'010427           ISZ      EC10
00606'006003- EC96:    JSR      @.PRN2
00607'006015- EC97:    JSR      @.GETT
00610'006003- EC98:    JSR      @.PRN2
00611'006020-          JSR      @.CHEK
00612'000405           JMP      EC95
00613'024422           LDA      1,EC11
00614'004411           JSR      EC50
00615'044420           STA      1,EC11
00616'002771           JMP      EC97
00617'024416  EC95:    LDA      1,EC11
00620'125120           MOVZL    1,1
00621'014413           DSZ      EC10
00622'125221           MOVZR    1,1,SKP
00623'124640           NEGOR    1,1
```

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---
00624'002407            JMP     @DBSAV
00625'131120  EC50:     MOVZL   1,2
00626'151120            MOVZL   2,2
00627'147000            ADD     2,1
00630'125120            MOVZL   1,1
00631'107000            ADD     0,1
00632'001400            JMP     0,3
00633'000000  DBSAV:    0
00634'000000  EC10:     0
00635'000000  EC11:     0
00636'000053  EC20:     "+
00637'000055  EC21:     "-
              ;
              ;TO CHECK IF ASCII BYTE IS A DIGIT
              ;& REDUCE IT TO BINARY IF IT IS
              ;         JSR @.CHEK
              ;         -- RETURNS HERE IF NOT DIGIT --
              ;         --    "       "   "  IS   "    --
              ;INPUT: AC0
              ;OUTPUT: AC0
              ;DESTROYED: AC1
              ;
00640'024412  CHEK:     LDA     1,MSK1
00641'123400            AND     1,0
00642'024412            LDA     1,N9
00643'122032            ADCZ#   1,0,SZC
00644'001400            JMP     0,3
00645'024406            LDA     1,N0
00646'106032            ADCZ#   0,1,SZC
00647'001400            JMP     0,3
00650'122400            SUB     1,0
00651'001401            JMP     1,3
00652'000177  MSK1:     177
00653'000060  N0:       "0
00654'000071  N9:       "9
              ;
              ;ROUTINE TO GET AN ALPHANUMERIC STRING FROM
              ;KEYBOARD AND STORE IT IN BYTE FORMAT WITH
              ;A TERMINATING ZERO BYTE
              ;
              ;         JSR @.WORD
              ;         ADDR   (ADDRESS TO PUT STRING)
              ;
              ;INPUT: FIRST CHARACTER IN AC0
              ;ALL ACCUMULATORS ARE LOST
              ;
00655'031400  WORD:     LDA     2,0,3    ;ADDR TO PUT STRING
00656'175400            INC     3,3
00657'054446            STA     3,WOSAV
00660'151120            MOVZL   2,2      ;BYTE POINTER
00661'050445            STA     2,TWP
00662'030445            LDA     2,MAXCS
00663'050445            STA     2,TRAP
00664'030442  MIKE:     LDA     2,TWP
00665'010441            ISZ     TWP
00666'024436            LDA     1,CR
00667'106415            SUB#    0,1,SNR
00670'000416            JMP     END1
00671'155220            MOVZR   2,3
00672'031400            LDA     2,0,3    ;OLD WORD
```

```
---
00673'024436            LDA     1,MSKL
00674'151002            MOV     2,2,SZC ;WHICH BYTE?
00675'151300            MOVS    2,2
00676'133400            AND     1,2
00677'113000            ADD     0,2     ;NEW BYTE
00700'151002            MOV     2,2,SZC
00701'151300            MOVS    2,2     ;SWAP BACK
00702'051400            STA     2,0,3   ;PUT BACK
00703'014425            DSZ     TRAP
00704'000415            JMP     MARK
00705'030421            LDA     2,TWP
00706'155220 END1:      MOVZR   2,3     ;PUT 0 IN LAST BYTE
00707'031400            LDA     2,0,3
00710'151002            MOV     2,2,SZC
00711'000404            JMP     LEFT
00712'152400            SUB     2,2
00713'051400            STA     2,0,3
00714'002411            JMP     @WOSAV
00715'024004S LEFT:     LDA     1,.MSKR
00716'133400            AND     1,2
00717'051400            STA     2,0,3
00720'002405            JMP     @WOSAV
00721'006015- MARK:     JSR     @.GETT
00722'006003-           JSR     @.PRN2
00723'000741            JMP     MIKE
00724'000015 CR:        15
00725'000000 WOSAV:     0
00726'000000 TWP:       0
00727'000020 MAXCS:     20
00730'000000 TRAP:      0
00731'177400 MSKL:      177400  ;L.H. MASK
                        .END
```

```
                        .TITL   LOADS
                        .ENT    .HEAVY
                        .EXTD   .NUM,.M1,.GETT,.DBIN,.MESS
                        .EXTD   .PRN2,.PAGE
                        .EXTN   CONTR
                        .ZREL
00000-000000' .HEAVY:   LOADS
                        .NREL
              ;
              ;  ROUTINE TO MULTIPLY OR DIVIDE ALL BLOCK
              ;  WEIGHTS (AREAS) BY A CONSTANT
              ;
00000'054526  LOADS:    STA     3,RTRN  ;SAVE ALL AC'S
00001'040526            STA     0,ZER
00002'044526            STA     1,ONE
00003'050526            STA     2,TWO
00004'006007$           JSR     @.PAGE
00005'006005$           JSR     @.MESS
00006'000155'           MS02
00007'177324            -300.
00010'001130            600.
              ;
              ;         CHECK FOR MULT / DIV
              ;
00011'006005$           JSR     @.MESS
00012'000172'           MS04
00013'000113            75.
00014'000702            450.
00015'006003$ OVR:      JSR     @.GETT
00016'040514            STA     0,DIG   ;STORE M OR D
00017'024514            LDA     1,MM
00020'106415            SUB#    0,1,SNR ;IS IT M ?
00021'000411            JMP     OUT
00022'024512            LDA     1,DD    ; IS IT D
00023'106415            SUB#    0,1,SNR
00024'000406            JMP     OUT
00025'006005$           JSR     @.MESS
00026'000227'           MS05
00027'000310            200.
00030'000651            425.
00031'000764            JMP     OVR
00032'006006$ OUT:      JSR     @.PRN2
00033'152400            SUB     2,2
00034'050504            STA     2,WHER
00035'024476            LDA     1,MM
00036'106415            SUB#    0,1,SNR
00037'000403            JMP     PAST
00040'152520            SUBZL   2,2
00041'050477            STA     2,WHER
              ;
              ;         GET CONSTANT
              ;
00042'006005$ PAST:     JSR     @.MESS
00043'000237'           MS06
00044'000226            150.
00045'000567            375.
00046'006004$           JSR     @.DBIN
00047'044472            STA     1,CNST  ;STORE CONSTANT
              ;
              ;         HERE WE GO !
```

```
                    ;
00050'034002S           LDA     3,.M1     ;GET 1ST BLOCK POINTER
00051'054464            STA     3,BLK
00052'024001S           LDA     1,.NUM    ;GET NO. OF BLOCKS
00053'044463            STA     1,CNT
00054'031400  OVR2:     LDA     2,0,3
00055'050462            STA     2,TEMP    ;SAVE FOR LATER
00056'021014            LDA     0,14,2    ;GET AREA
00057'101005            MOV     0,0,SNR   ;SKIP ERASED BLOCK
00060'000425            JMP     TRAP
00061'024457            LDA     1,WHER
00062'125004            MOV     1,1,SZR   ;IF NOT 0 DIVIDE
00063'000412            JMP     DIVD
00064'111000  MULT:     MOV     0,2
00065'102400            SUB     0,0
00066'024453            LDA     1,CNST
00067'073301            MUL
00070'030447            LDA     2,TEMP
00071'045014            STA     1,14,2    ;STORE NEW "AREA"
00072'125132            MOVZL#  1,1,SZC   ;TEST FOR >77777
00073'000426            JMP FAIL
00074'000411            JMP     TRAP
00075'105000  DIVD:     MOV     0,1       ;AREA IN AC1
00076'102400            SUB     0,0       ;CLEAR HI PART
00077'030442            LDA     2,CNST
00100'132432            SUBZ#   1,2,SZC   ; DIV TEST
00101'000420            JMP     FAIL
00102'073101            DIV
00103'030434            LDA     2,TEMP
00104'045014            STA     1,14,2
00105'010430  TRAP:     ISZ     BLK
00106'034427            LDA     3,BLK
00107'014427            DSZ     CNT
00110'000744            JMP     OVR2      ;DO NEXT BLOCK
00111'020416            LDA     0,ZER
00112'024416            LDA     1,ONE
00113'030416            LDA     2,TWO
00114'006005S           JSR     @.MESS
00115'000252'           MS09
00116'177160            -400.
00117'000372            250.
00120'002422            JMP     @CON
00121'006005S FAIL:     JSR     @.MESS
00122'000143'           MS08
00123'177470            -200.
00124'000310            200.
00125'002415            JMP     @CON
00126'000000  RTRN:     0
00127'000000  ZER:      0
00130'000000  ONE:      0
00131'000000  TWO:      0
00132'000000  DIG:      0
00133'000115  MM:       "M
00134'000104  DD:       "D
00135'000000  BLK:      0
00136'000000  CNT:      0
00137'000000  TEMP:     0
00140'000000  WHER:     0
00141'000000  CNST:     0
00142'177777  CON:      CONTR
```

---

```
                    ;
00143'040506  MS08:    .TXT     *FA
00144'046111  IL
00145'042105  ED
00146'051454  ,S
00147'040524  TA
00150'052122  RT
00151'040440   A
00152'020124  T
00153'026520  P-
00154'000061  1*
00155'046102  MS02:    .TXT     *BL
00156'041517  OC
00157'020113  K
00160'042527  WE
00161'043511  IG
00162'052110  HT
00163'046440   M
00164'042117  OD
00165'043111  IF
00166'041511  IC
00167'052101  AT
00170'047511  IO
00171'000116  N*
00172'047504  MS04:    .TXT     *DO
00173'054440   Y
00174'052517  OU
00175'053440   W
00176'051511  IS
00177'020110  H
00200'047524  TO
00201'046440   M
00202'046125  UL
00203'044524  TI
00204'046120  PL
00205'020131  Y
00206'046450  (M
00207'020051  )
00210'051117  OR
00211'042040   D
00212'053111  IV
00213'042111  ID
00214'020105  E
00215'042050  (D
00216'020051  )
00217'044124  TH
00220'020105  E
00221'042527  WE
00222'043511  IG
00223'052110  HT
00224'020123  S
00225'020077  ?
00226'000000  *
00227'052515  MS05:    .TXT     *MU
00230'052123  ST
00231'041040   B
00232'020105  E
00233'020115  M
00234'051117  OR
00235'042040   D
```

```
00236'000040   *
00237'044127  MS06:    .TXT     *WH
00240'052101  AT
00241'044440   I
00242'020123  S
00243'044124  TH
00244'020105  E
00245'040506  FA
00246'052103  CT
00247'051117  OR
00250'037440   ?
00251'000040   *
00252'047503  MS09:    .TXT     *CO
00253'050115  MP
00254'042514  LE
00255'042524  TE
00256'026104  D,
00257'053440   W
00260'044501  AI
00261'044524  TI
00262'043516  NG
00263'040040   @
00264'041440   C
00265'047117  ON
00266'051124  TR
00267'000000  *
                       .END
```

---

```
                        .TITL   FORD
                  ;FORCE-DISPLACEMENT LAW FOR ALL
                  ;CONTACT POINTS
                        .EXTD   .M1,.M5,.NUM,.EMPT,.MSKR
                        .EXTD   .VEC,.SCAL,.PLTS,.SPRP,.PRES
                        .EXTD   .MESS,.GETT,.IPRN
                        .EXTD   .ROT,.UREP,.TREC
                        .EXTD   .NVEC,.PAGE,.ALPH,.HEAVY
                        .EXTN   CONTR
                        .ENT    .FORD,.TIME,MU
                        .ZREL
00000-000000  MU:       000000  ;FRICTION COEF. (DEFAULT VALUE = .0)
00001-000033' .FORD:    FORD
00002-000001  .KDN:     1       ;NORMAL DAMPING FACTOR
00003-000001  .KDS:     1       ;SHEAR DAMPING FACTOR
00004-000000  XCP:      0
00005-000000  YCP:      0
00006-000000  DELS:     0
00007-000000  DELN:     0
00010-000000  FN:       0
00011-000000  FDSAV:    0
00012-000000  LOCPR:    0
00013-000000  LOCBL:    0
00014-000000  LOCBP:    0
00015-000000  OLINK:    0
00016-000000  COUNT:    0
00017-000000  PRLNK:    0
00020-000000  COS:      0
00021-000000  SIN:      0
00022-000000  COSF:     0
00023-000000  SINF:     0
00024-000672' .TIME:    DYNFAC
                        .NREL
00000'102440  MULS:     SUBO    0,0
00001'050420            STA     2,SV2
00002'027400            LDA     @1,0,3   ;A
00003'033401            LDA     @2,1,3   ;B
00004'125112            MOVL#   1,1,SZC
00005'124460            NEGC    1,1
00006'151112            MOVL#   2,2,SZC
00007'150460            NEGC    2,2
00010'073301            MUL
00011'030005S           LDA     2,.MSKR
00012'143700            ANDS    2,0      ;TAKE MIDDLE 8 BITS
00013'125300            MOVS    1,1
00014'147400            AND     2,1
00015'107002            ADD     0,1,SZC
00016'124400            NEG     1,1
00017'030402            LDA     2,SV2
00020'001402            JMP     2,3      ;A*B IN AC1
00021'000000  SV2:      0
              ;
00022'000000  XDL:      0
00023'000000  YDL:      0
00024'000000  XDP:      0
00025'000000  YDP:      0
00026'000000  DAP:      0
00027'000000  DAL:      0
00030'000000  DXL:      0
00031'000000  DYL:      0
```

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```
                    ;
00032'000310' NEXTR:   NEXTB
00033'054011- FORD:    STA      3,FDSAV
00034'034002$          LDA      3,.M5     ;INITIAL PROD POINTER
00035'054012-          STA      3,LOCPR
00036'054015-          STA      3,OLINK
00037'020003$          LDA      0,.NUM
00040'040016-          STA      0,COUNT
00041'034001$          LDA      3,.M1     ;INITIAL BLOCK DAT. PNTR.
00042'054013-          STA      3,LOCBL
00043'036012- LOOP:    LDA      3,@LOCPR         ;1ST WORD
00044'175112  ENTRY:   MOVL#    3,3,SZC ;LIST TAIL FLAG?
00045'002765           JMP      @NEXTR   ;YES, NEXT BLOCK
00046'054017-          STA      3,PRLNK
00047'021400           LDA      0,0,3    ;CONTROL WORD
00050'040023-          STA      0,SINF   ;SIN FLAG IN BIT 0
00051'101100           MOVL     0,0
00052'040022-          STA      0,COSF   ;COS FLAG IN BIT 0
00053'021410           LDA      0,10,3   ;SIN
00054'040021-          STA      0,SIN
00055'021411           LDA      0,11,3   ;COS
00056'040020-          STA      0,COS
00057'021412           LDA      0,12,3
00060'040004-          STA      0,XCP    ;X CONTACT POINT
00061'021413           LDA      0,13,3
00062'040005-          STA      0,YCP    ;Y CONTACT POINT
                    ;TO GET CONTRIBUTIONS FROM EDGE
00063'032013-          LDA      2,@LOCBL
00064'021001           LDA      0,1,2    ;XG, THIS BLOCK
00065'024004-          LDA      1,XCP
00066'106400           SUB      0,1
00067'044733           STA      1,XDL
00070'021003           LDA      0,3,2    ;YG, THIS BLOCK
00071'024005-          LDA      1,YCP
00072'106400           SUB      0,1
00073'044730           STA      1,YDL
00074'021022           LDA      0,22,2
00075'040732           STA      0,DAL
00076'004702           JSR      MULS
00077'000027'          DAL
00100'000023'          YDL
00101'021020           LDA      0,20,2   ;DELTA-X, THIS BLOCK
00102'122400           SUB      1,0      ;SUBTRACT ROT. CONTRIB.
00103'040725           STA      0,DXL
00104'004674           JSR      MULS
00105'000027'          DAL
00106'000022'          XDL
00107'021021           LDA      0,21,2   ;DELTA-Y
00110'123000           ADD      1,0
00111'040720           STA      0,DYL
                    ;
00112'034017-          LDA      3,PRLNK
00113'021401           LDA      0,1,3    ;(NP:NB)
00114'024005$          LDA      1,.MSKR
00115'107400           AND      0,1      ;BLOCK # OF POINT
00116'030001$          LDA      2,.M1
00117'133000           ADD      1,2
00120'050014-          STA      2,LOCBP ;DATA POINTER (POINT)
00121'031000           LDA      2,0,2
00122'021001           LDA      0,1,2    ;XG, OTHER BLOCK
```

```
00123'024004-          LDA    1,XCP
00124'106400           SUB    0,1
00125'044677           STA    1,XDP
00126'021003           LDA    0,3,2    ;YG, OTHER BLOCK
00127'024005-          LDA    1,YCP
00130'106400           SUB    0,1
00131'044674           STA    1,YDP
00132'021022           LDA    0,22,2
00133'040673           STA    0,DAP    ;DELTA-ALPHA
00134'004644           JSR    MULS
00135'000026'          DAP
00136'000025'          YDP
00137'021020           LDA    0,20,2   ;DELTA-X, NB(P)
00140'122400           SUB    1,0
00141'024667           LDA    1,DXL
00142'122400           SUB    1,0      ;DXP-DXL
00143'040570           STA    0,DELX
00144'004634           JSR    MULS
00145'000026'          DAP
00146'000024'          XDP
00147'021021           LDA    0,21,2   ;DYP
00150'123000           ADD    1,0
00151'024660           LDA    1,DYL
00152'122400           SUB    1,0      ;DYP-DYL
00153'040561           STA    0,DELY
00154'004562           JSR    TRANS    ;TRANSFORMATION ROUTINE
00155'030017-          LDA    2,PRLNK
00156'021005           LDA    0,5,2    ;OLD N (NORM. DISP.)
00157'163000           ADD    3,0
00160'041005           STA    0,5,2    ;NEW N
00161'165000           MOV    3,1
00162'030553           LDA    2,KN     ;NORMAL STIFFNESS
00163'102400           SUB    0,0
00164'125112           MOVL#  1,1,SZC
00165'124400           NEG    1,1
00166'073301           MUL
00167'175113           MOVL#  3,3,SNC
00170'124400           NEG    1,1      ;INVERT ORIG. SIGN
00171'030017-          LDA    2,PRLNK ;  FOR +VE FN
00172'021006           LDA    0,6,2    ;OLD NORMAL FORCE, FN
00173'125112           MOVL#  1,1,SZC
00174'000405           JMP    OK
00175'107000           ADD    0,1
00176'125112           MOVL#  1,1,SZC
00177'006506           JSR    @LM1
00200'000404           JMP    STOR
00201'107000    OK:    ADD    0,1      ;ADD IN INCREMENT
00202'125112           MOVL#  1,1,SZC ;ZERO ADHESION ASSUMED
00203'000520           JMP    DELET    ;SET FORCES TO ZERO
00204'045006    STOR:  STA    1,6,2    ;NEW NORMAL FORCE
00205'044010-          STA    1,FN
00206'165000           MOV    3,1
00207'030002-          LDA    2,.KDN   ;DAMPING FACTOR
00210'102400           SUB    0,0
00211'125112           MOVL#  1,1,SZC
00212'124400           NEG    1,1
00213'073301           MUL
00214'175113           MOVL#  3,3,SNC
00215'124400           NEG    1,1
00216'020010-          LDA    0,FN
```

```
---
00217'123000            ADD     1,0
00220'125112            MOVL#   1,1,SEC
00221'000403            JMP     NC
00222'101112            MOVL#   0,0,SEC
00223'006463            JSR     @LM0
00224'040510  NC:       STA     0,DELY
              ;
00225'030017-           LDA     2,PRLNK
00226'006501            JSR     @SHR    ;GET SHEAR FORCE
              ;
00227'040504            STA     0,DELX
00230'004506            JSR     TRANS
              ;ADD GLOBAL FORCES ARISING FROM
              ;THIS CONTACT.
00231'006453            JSR     @MOMT   ;MOMENT, THIS BLOCK
00232'000007-           DELN
00233'000006-           DELS
00234'000022'           XDL
00235'000023'           YDL
00236'032013-           LDA     2,@LOCBL        ;THIS BLOCK
00237'021017            LDA     0,17,2
00240'122400            SUB     1,0
00241'041017            STA     0,17,2  ;NEW MSUM
00242'021007            LDA     0,7,2   ;OLD FXSUM
00243'024006-           LDA     1,DELS
00244'123000            ADD     1,0
00245'041007            STA     0,7,2   ;NEW FXSUM
00246'021016            LDA     0,16,2  ;OLD FYSUM
00247'024007-           LDA     1,DELN
00250'122400            SUB     1,0
00251'041016            STA     0,16,2  ;NEW FYSUM
00252'006432            JSR     @MOMT
00253'000007-           DELN
00254'000006-           DELS
00255'000024'           XDP
00256'000025'           YDP
00257'032014-           LDA     2,@LOCBP        ;OTHER BLOCK
00260'021017            LDA     0,17,2  ;OLD    MSUM
00261'123000            ADD     1,0
00262'041017            STA     0,17,2  ;NEW MSUM
00263'021007            LDA     0,7,2   ;AS ABOVE, BUT
00264'024006-           LDA     1,DELS  ; WITH OPPOSITE SIGNS
00265'122400            SUB     1,0
00266'041007            STA     0,7,2
00267'021016            LDA     0,16,2
00270'024007-           LDA     1,DELN
00271'123000            ADD     1,0
00272'041016            STA     0,16,2
00273'020006S           LDA     0,.VEC  ;PLOT VECTORS IF FLAG SET
00274'101004            MOV     0,0,SZR
00275'006412            JSR     @VDISP
00276'034017- CHAIN:    LDA     3,PRLNK
00277'171400            INC     3,2
00300'151400            INC     2,2     ;GET LINK ADDRESS
00301'050015-           STA     2,OLINK ;REVERSE LINK
00302'035402            LDA     3,2,3
00303'002425            JMP     @ENTR   ;GET NEXT ENTRY
00304'000432' MOMT:     MOM
00305'001143' LM1:      LIM1
00306'001150' LM0:      LIM0
---
```

```
---
00307'000503' VDISP:  VDIS
               ;NEXT BLOCK
00310'010012- NEXTR:  ISZ      LOCPR    ;INCR. PROD LOCATOR
00311'034012-         LDA      3,LOCPR
00312'054015-         STA      3,OLINK
00313'010013-         ISZ      LOCBL    ;INCR. DATA LOCATOR
00314'014016-         DSZ      COUNT    ;EXIT IF ALL BLOCKS
00315'002414          JMP      @LOOPR   ;   SCANNED
00316'030012S         LDA      2,.PRES
00317'151112          MOVL#    2,2,SZC
00320'002011-         JMP      @FDSAV   ;NO PRESS. SEGMENTS
00321'002401          JMP      @PRS     ;GET FORCES FROM PR. SEGS.
00322'000637' PRS:    PRESU
00323'102400  DELET:  SUB      0,0
00324'041006          STA      0,6,2
00325'041007          STA      0,7,2
00326'000750          JMP      CHAIN
00327'000553' SHR:    SHEAR
00330'000044' ENTR:   ENTRY
00331'000043' LOOPR:  LOOP
00332'000000  SAVE:   0
00333'000000  DELX:   0
00334'000000  DELY:   0
00335'000003  KN:     3
00336'054774  TRANS:  STA      3,SAVE
00337'024774          LDA      1,DELX
00340'030020-         LDA      2,COS
00341'102440          SUBO     0,0      ;CLEAR CARRY
00342'125112          MOVL#    1,1,SZC
00343'124440          NEGO     1,1      ;SET CARRY
00344'073301          MUL               ;DELX*COS
00345'125112          MOVL#    1,1,SZC ;ROUND UP IF NEC.
00346'101400          INC      0,0
00347'101002          MOV      0,0,SZC
00350'100400          NEG      0,0      ;RESTORE SIGN
00351'024022-         LDA      1,COSF
00352'125102          MOVL     1,1,SZC
00353'100400          NEG      0,0
00354'115000          MOV      0,3      ;PARTIAL SUM IN AC3
00355'024757          LDA      1,DELY
00356'030021-         LDA      2,SIN
00357'102440          SUBO     0,0
00360'125112          MOVL#    1,1,SZC
00361'124440          NEGO     1,1
00362'073301          MUL               ;DELY*SIN
00363'125112          MOVL#    1,1,SZC ;ROUND UP IF NEC.
00364'101400          INC      0,0
00365'101002          MOV      0,0,SZC
00366'100400          NEG      0,0
00367'024023-         LDA      1,SINF
00370'125102          MOVL     1,1,SZC
00371'100400          NEG      0,0
00372'117000          ADD      0,3      ;DELX*COS+DELY*SIN
00373'054006-         STA      3,DELS
00374'024740          LDA      1,DELY
00375'030020-         LDA      2,COS
00376'102440          SUBO     0,0
00377'125112          MOVL#    1,1,SZC
00400'124440          NEGO     1,1
00401'073301          MUL               ;DELY*COS
---
```

```
00402'125112         MOVL#   1,1,SZC ;ROUND UP IF NEC.
00403'101400         INC     0,0
00404'101002         MOV     0,0,SZC
00405'100400         NEG     0,0
00406'024022-        LDA     1,COSF
00407'125102         MOVL    1,1,SZC
00410'100400         NEG     0,0
00411'115000         MOV     0,3     ;PARTIAL SUM IN AC3
00412'024721         LDA     1,DELX
00413'030021-        LDA     2,SIN
00414'102440         SUBO    0,0
00415'125112         MOVL#   1,1,SZC
00416'124440         NEGO    1,1
00417'073301         MUL             ;DELX*SIN
00420'125112         MOVL#   1,1,SZC ;ROUND UP IF NEC.
00421'101400         INC     0,0
00422'101002         MOV     0,0,SZC
00423'100400         NEG     0,0
00424'024023-        LDA     1,SINF
00425'125102         MOVL    1,1,SZC
00426'100400         NEG     0,0
00427'116400         SUB     0,3     ;DELY*COS-DELX*SIN
00430'054007-        STA     3,DELN
00431'002701         JMP     @SAVE
               ;COMPUTES A*XDIF+B*YDIF , AND TRUNCATES
               ;TO MIDDLE 16 BITS OF 32 BIT NUMBER
               ;    OUTPUT: AC1
00432'054444   MOM:  STA     3,TEMP
00433'027400         LDA     @1,0,3  ;A
00434'033402         LDA     @2,2,3  ;XDIF
00435'176400         SUB     3,3
00436'125112         MOVL#   1,1,SZC
00437'157000         ADD     2,3
00440'151112         MOVL#   2,2,SZC
00441'137000         ADD     1,3
00442'102400         SUB     0,0
00443'073301         MUL
00444'162400         SUB     3,0
00445'040432         STA     0,HI    ;A*XDIF IN AC0:AC1
00446'044432         STA     1,LO
00447'034427         LDA     3,TEMP
00450'027401         LDA     @1,1,3  ;B
00451'033403         LDA     @2,3,3  ;YDIF
00452'176400         SUB     3,3
00453'125112         MOVL#   1,1,SZC
00454'157000         ADD     2,3
00455'151112         MOVL#   2,2,SZC
00456'137000         ADD     1,3
00457'102400         SUB     0,0
00460'073301         MUL
00461'162400         SUB     3,0     ;B*YDIF IN AC0:AC1
00462'030415         LDA     2,HI
00463'034415         LDA     3,LO
00464'167022         ADDZ    3,1,SZC ;ADD 2 D.P. NUMBERS
00465'151400         INC     2,2
00466'143000         ADD     2,0     ;D.P. ANSWER IN AC0:AC1
00467'030005S        LDA     2,.MSKR ;NOW TAKE ONLY MIDDLE
00470'143700         ANDS    2,0     ; 8 BITS
00471'125300         MOVS    1,1
00472'147400         AND     2,1
```

```
00473'107000          ADD     0,1      ;RESULT IN AC1
00474'034402          LDA     3,TEMP
00475'001404          JMP     4,3      ;RETURN TO CALL +5
00476'000000  TEMP:   0
00477'000000  HI:     0
00500'000000  LO:     0
00501'000000  XNUM:   0
00502'000000  YNUM:   0
00503'054446  VDIS:   STA     3,VEC3   ;VECTOR PLOTTING ROUTINE
00504'020004-         LDA     0,XCP    ;X CONTACT POINT
00505'024005-         LDA     1,YCP    ;Y     "
00506'006010S         JSR     @.PLTS   ;1ST END (BEAM OFF)
00507'000000          0
00510'024006-         LDA     1,DELS
00511'044770          STA     1,XNUM
00512'006007S         JSR     @.SCAL   ;SCALE FORCE FOR PLOTTING
00513'020004-         LDA     0,XCP
00514'123000          ADD     1,0
00515'040435          STA     0,XVEC   ;X VECTOR
00516'024007-         LDA     1,DELN
00517'044763          STA     1,YNUM
00520'006007S         JSR     @.SCAL
00521'020005-         LDA     0,YCP
00522'122400          SUB     1,0
00523'105000          MOV     0,1      ;Y VECTOR
00524'020426          LDA     0,XVEC
00525'006010S         JSR     @.PLTS   ;PLOT VECTOR
00526'000001          1                ;BEAM ON
00527'006023S         JSR     @.ALPH
00530'030021S         LDA     2,.NVEC  ;TO PRINT VALUES
00531'151005          MOV     2,2,SNR  ;0=DONT PRINT
00532'002417          JMP     @VEC3
00533'020746          LDA     0,XNUM
00534'006015S         JSR     @.IPRN   ;PRINT X
00535'000005          5
00536'020744          LDA     0,YNUM
00537'006015S         JSR     @.IPRN   ;PRINT Y
00540'000005          5
00541'030021S         LDA     2,.NVEC  ;IF>1,HALT FOR CHECK
00542'151224          MOVZR   2,2,SZR
00543'004402          JSR     WAIT     ;WAIT FOR ANY KEY
00544'002405          JMP     @VEC3
00545'063610  WAIT:   SKPDN   TTI
00546'000777          JMP     .-1
00547'060210          NIOC    TTI
00550'001400          JMP     0,3
00551'000000  VEC3:   0
00552'000000  XVEC:   0
              ;
              ;THE FOLLOWING ROUTINE COMPUTES SHEAR FORCE
              ;FROM SHEAR DISP. AND NORMAL FORCE.
              ;IT ALSO ADDS IN DAMPING TERM, IF CONTACT IS
              ;NOT SLIDING.
              ;
00553'050455  SHEAR:  STA     2,SVS2
00554'025000          LDA     1,0,2
00555'020455          LDA     0,FRMSK  ;TYPE # MASK
00556'107704          ANDS    0,1,SZR  ;IF ZERO, USE DEFAULT
00557'000454          JMP     GETFR
00560'030000-         LDA     2,MU     ;FRICTION COEF (<1)
```

```
00561'024010- SLIP:   LDA     1,FN
00562'102400          SUB     0,0
00563'073301          MUL             ;FN*MU IN AC0
00564'040443          STA     0,FSMAX ;MAX POSS SHEAR FORCE
00565'030444          LDA     2,KS    ;SHEAR STIFFNESS
00566'024006-         LDA     1,DELS  ;INCR. SHEAR DISP.
00567'102440          SUBO    0,0     ;CLEAR CARRY
00570'125112          MOVL#   1,1,SZC
00571'124440          NEGO    1,1     ;SET CARRY IF DELS -VE
00572'073301          MUL             ;DELS*KS (=DELTA[FS])
00573'125002          MOV     1,1,SZC
00574'124400          NEG     1,1     ;RETURN SIGN
00575'030433          LDA     2,SVS2
00576'021007          LDA     0,7,2   ;FS(OLD)
00577'107000          ADD     0,1     ;RAW FS
00600'044426          STA     1,FS
                ;
                ; THE FOLLOWING LINE WAS IN ERROR IN PAC'S
00601'045007          STA     1,7,2   ;7/30/76 ERROR FOUND
                ;
00602'121102          MOVL    1,0,SZC
00603'124400          NEG     1,1
00604'020423          LDA     0,FSMAX
00605'122513          SUBL#   1,0,SNC ;EXCEEDED MAX?
00606'000405          JMP     DAMP    ;NO. ADD IN DAMPING
00607'125002          MOV     1,1,SZC ;SIGN?
00610'100400          NEG     0,0
00611'041007          STA     0,7,2   ;NEW FS IN AC0
00612'001400          JMP     0,3     ;EXIT
00613'024006- DAMP:   LDA     1,DELS
00614'030003-         LDA     2,.KDS  ;DAMPING FACTOR
00615'102440          SUBO    0,0
00616'125112          MOVL#   1,1,SZC
00617'124440          NEGO    1,1
00620'073301          MUL
00621'125002          MOV     1,1,SZC
00622'124400          NEG     1,1
00623'020403          LDA     0,FS
00624'123000          ADD     1,0     ;ADD IN DAMPING FORCE
00625'001400          JMP     0,3     ;EXIT (OUTPUT: AC0)
00626'000000  FS:     0
00627'000000  FSMAX:  0
00630'000000  SVS2:   0
00631'000003  KS:     3       ;SHEAR STIFFNESS
00632'017400  FRMSK:  17400   ;MASK FOR TYPE # PART OF CONT. WORD
00633'030011S GETFR:  LDA     2,.SPRP
00634'133000          ADD     1,2
00635'031000          LDA     2,0,2   ;GET APPROPRIATE FRICTION
00636'000723          JMP     SLIP
                ;
                ;TO ADD IN PRESSURE FORCES FROM LINKED
                ;LIST OF PRESSURE SEGMENTS.
                ;
00637'021000  PRESU:  LDA     0,0,2
00640'024005S         LDA     1,.MSKR
00641'123400          AND     1,0     ;NB
00642'034001S         LDA     3,.M1
00643'117000          ADD     0,3
00644'035400          LDA     3,0,3   ;BLOCK POINTER
                ;-----
```

```
00645'021003          LDA     0,3,2   ;M INCREMENT
00646'025417          LDA     1,17,3  ;OLD MSUM
00647'107000          ADD     0,1
00650'045417          STA     1,17,3  ;NEW MSUM
                ;-----
00651'021004          LDA     0,4,2   ;FX INCREMENT
00652'025407          LDA     1,7,3   ;OLD FXSUM
00653'107000          ADD     0,1
00654'045407          STA     1,7,3   ;NEW FXSUM
                ;-----
00655'021005          LDA     0,5,2   ;FY INCREMENT
00656'025416          LDA     1,16,3  ;OLD FYSUM
00657'107000          ADD     0,1
00660'045416          STA     1,16,3  ;NEW FYSUM
                ;-----
00661'031002          LDA     2,2,2   ;LINK
00662'151115          MOVL#   2,2,SNR
00663'000754          JMP     PRESU
00664'002011-         JMP     @FDSAV  ;END OF CHAIN.
                ;---------------
                ; ROUTINE TO CHANGE TREC, ETC.
                ;
00665'000040    DTREC:  40
00666'000001    DKDN:   1
00667'000012    DKDS:   12
00670'000140    DROT:   140
00671'000023    DUREP:  23
                ;
00672'006022$   DYNFAC: JSR     @.PAGE
00673'006023$           JSR     @.ALPH
00674'006013$           JSR     @.MESS
00675'001212'           DMS0
00676'177470            -200.
00677'001320            720.
00700'006013$           JSR     @.MESS
00701'001234'           DMS1
00702'177665            -75.
00703'001236            670.
00704'006013$           JSR     @.MESS
00705'001244'           DMS2
00706'000175            125.
00707'001200            640.
00710'020020$           LDA     0,.TREC ;TIME STEP
00711'006015$           JSR     @.IPRN
00712'000004            4
00713'006013$           JSR     @.MESS
00714'001250'           DMS3
00715'000175            125.
00716'001130            600.
00717'020002-           LDA     0,.KDN  ;NORMAL DAMPING FAC
00720'006015$           JSR     @.IPRN
00721'000004            4
00722'006013$           JSR     @.MESS
00723'001254'           DMS4
00724'000175            125.
00725'001060            560.
00726'020003-           LDA     0,.KDS  ;SHEAR DAMPING FAC
00727'006015$           JSR     @.IPRN
00730'000004            4
00731'006013$           JSR     @.MESS
```

```
00732'001260'          DMS5
00733'000175           125.
00734'001010           520.
00735'020016$          LDA     0,.ROT   ;ROT. TIME FAC
00736'006015$          JSR     @.IPRN
00737'000005           5
00740'006013$          JSR     @.MESS
00741'001264'          DMS6
00742'000175           125.
00743'000740           480.
00744'020017$          LDA     0,.UREP ;UPDATE COUNTER
00745'006015$          JSR     @.IPRN
00746'000004           4
                ;
00747'006013$          JSR     @.MESS
00750'001270'          DMS7
00751'177470           -200.
00752'000536           350.
00753'006013$          JSR     @.MESS
00754'001306'          DMS8
00755'000454           300.
00756'000454           300.
00757'006013$          JSR     @.MESS
00760'001325'          DMS9
00761'000454           300.
00762'000404           260.
00763'006013$          JSR     @.MESS
00764'001367'          DM10
00765'000454           300.
00766'000334           220.
00767'006013$          JSR     @.MESS
00770'001344'          DMS10
00771'000454           300.
00772'000264           180.
                ;
                ; GET CONTROL KEY
                ;
00773'006014$          JSR     @.GETT
00774'024414           LDA     1,WCHR   ;IS IT A W
00775'106415           SUB#    0,1,SNR
00776'006024$          JSR     @.HEAVY ;YES
00777'024407           LDA     1,ICHR   ;IS IT AN I?
01000'106415           SUB#    0,1,SNR
01001'000410           JMP     UP       ;YES
01002'024405           LDA     1,DCHR   ;IS IT A D ?
01003'106415           SUB#    0,1,SNR
01004'000434           JMP     DWN      ;YES
01005'002535           JMP     @CON     ;NONE-GO TO CONTR
01006'000111  ICHR:    "I
01007'000104  DCHR:    "D
01010'000127  WCHR:    "W
01011'020002- UP:      LDA     0,.KDN
01012'024654           LDA     1,DKDN
01013'106432           SUBZ#   0,1,SZC ;IFKDN=DKDN ALREADY AT MAX
01014'000521           JMP     MAX
01015'122400           SUB     1,0
01016'040002-          STA     0,.KDN
01017'020020$          LDA     0,.TREC
01020'024645           LDA     1,DTREC
01021'122400           SUB     1,0
```

```
---
01022'040020$          STA     0,.TREC
01023'020003-          LDA     0,.KDS
01024'024643           LDA     1,DKDS
01025'122400           SUB     1,0
01026'040003-          STA     0,.KDS
01027'020016$          LDA     0,.ROT
01030'024640           LDA     1,DROT
01031'122400           SUB     1,0
01032'040016$          STA     0,.ROT
01033'020017$          LDA     0,.UREP
01034'024635           LDA     1,DUREP
01035'122400           SUB     1,0
01036'040017$          STA     0,.UREP
01037'000426           JMP     OUTPT
                ;
01040'020020$ DWN:     LDA     0,.TREC
01041'024624           LDA     1,DTREC
01042'107000           ADD     0,1
01043'044020$          STA     1,.TREC
01044'020002-          LDA     0,.KDN
01045'024621           LDA     1,DKDN
01046'107000           ADD     0,1
01047'044002-          STA     1,.KDN
01050'020003-          LDA     0,.KDS
01051'024616           LDA     1,DKDS
01052'107000           ADD     0,1
01053'044003-          STA     1,.KDS
01054'020016$          LDA     0,.ROT
01055'024613           LDA     1,DROT
01056'107000           ADD     0,1
01057'044016$          STA     1,.ROT
01060'020017$          LDA     0,.UREP
01061'024610           LDA     1,DUREP
01062'107000           ADD     0,1
01063'044017$          STA     1,.UREP
01064'000401           JMP     OUTPT
                ;
01065'006013$ OUTPT:   JSR     @.MESS
01066'001361'          DMS11
01067'176701           -575.
01070'001236           670.
01071'006013$          JSR     @.MESS
01072'001244'          DMS2
01073'001161           625.
01074'001200           640.
01075'020020$          LDA     0,.TREC
01076'006015$          JSR     @.IPRN
01077'000004           4
01100'006013$          JSR     @.MESS
01101'001250'          DMS3
01102'001161           625.
01103'001130           600.
01104'020002-          LDA     0,.KDN
01105'006015$          JSR     @.IPRN
01106'000004           4
01107'006013$          JSR     @.MESS
01110'001254'          DMS4
01111'001161           625.
01112'001060           560.
01113'020003-          LDA     0,.KDS
---
```

```
01114'006015$           JSR     @.IPRN
01115'000004            4
01116'006013$           JSR     @.MESS
01117'001260'           DMS5
01120'001161            625.
01121'001010            520.
01122'020016$           LDA     0,.POT
01123'006015$           JSR     @.IPRN
01124'000005            5
01125'006013$           JSR     @.MESS
01126'001264'           DMS6
01127'001161            625.
01130'000740            480.
01131'020017$           LDA     0,.UREP
01132'006015$           JSR     @.IPRN
01133'000004            4
01134'002406            JMP     @CON
                ;
                ;
01135'006013$ MAX:      JSR     @.MESS
01136'001172'           ERR
01137'177470            -200.
01140'000226            150.
01141'002401            JMP     @CON     ; GO BACK TO CONTR
01142'177777  CON:      CONTR
                ;
01143'054411  LIM1:     STA     3,RETN
01144'004412            JSR     WARN
01145'024410            LDA     1,LIMIT
01146'034007-           LDA     3,DELN
01147'002405            JMP     @RETN
01150'054404  LIM0:     STA     3,RETN
01151'004405            JSR     WARN
01152'020403            LDA     0,LIMIT
01153'002401            JMP     @RETN
                ;
01154'000000  RETN:     0
01155'077777  LIMIT:    77777   ;MAX NORMAL FORCE
                ;
01156'054413  WARN:     STA     3,RETR
01157'006013$           JSR     @.MESS
01160'001404'           MW1
01161'001522            850.
01162'001332            730.
01163'006013$           JSR     @.MESS
01164'001412'           MW2
01165'001522            850.
01166'001313            715.
01167'034402            LDA     3,RETR
01170'001400            JMP     0,3
01171'000000  RETR:     0
                ;
01172'047523  ERR:      .TXT    *SO
01173'051122  RR
01174'026131  Y,
01175'046101  AL
01176'042522  RE
01177'042101  AD
01200'020131  Y
01201'052101  AT
```

```
01202'046440   M
01203'054101  AX
01204'046511  IM
01205'046525  UM
01206'053040   V
01207'046101  AL
01210'042525  UE
01211'000123  S*
01212'027056  DMS0:    .TXT     *..
01213'027056  ..
01214'027056  ..
01215'020056  .
01216'054504  DY
01217'040516  NA
01220'044515  MI
01221'020103  C
01222'040520  PA
01223'040522  RA
01224'042515  ME
01225'042524  TE
01226'051522  RS
01227'027056  ..
01230'027056  ..
01231'027056  ..
01232'027056  ..
01233'000000  *
01234'051120  DMS1:    .TXT     *PR
01235'051505  ES
01236'047105  EN
01237'020124  T
01240'040526  VA
01241'052514  LU
01242'051505  ES
01243'000000  *
01244'052056  DMS2:    .TXT     *.T
01245'042522  RE
01246'020103  C
01247'000075  =*
01250'045456  DMS3:    .TXT     *.K
01251'047104  DN
01252'036440   =
01253'000000  *
01254'045456  DMS4:    .TXT     *.K
01255'051504  DS
01256'036440   =
01257'000000  *
01260'051056  DMS5:    .TXT     *.R
01261'052117  OT
01262'036440   =
01263'000000  *
01264'052456  DMS6:    .TXT     *.U
01265'042522  RE
01266'020120  P
01267'000075  =*
01270'047506  DMS7:    .TXT     *FO
01271'051125  UR
01272'047440   O
01273'052120  PT
01274'047511  IO
01275'051516  NS
```

```
01276'040440   A
01277'040526  VA
01300'046111  ıL
01301'041101  AB
01302'042514  LE
01303'026440   -
01304'026455  --
01305'000040   *
01306'054524  DMS8:    .TXT     *TY
01307'042520  PE
01310'044440   I
01311'052040   T
01312'020117  O
01313'047111  IN
01314'051103  CR
01315'040505  EA
01316'042523  SE
01317'052040   T
01320'046511  IM
01321'020105  E
01322'052123  ST
01323'050105  EP
01324'000000  *
01325'054524  DMS9:    .TXT     *TY
01326'042520  PE
01327'042040   D
01330'052040   T
01331'020117  O
01332'042504  DE
01333'051103  CR
01334'040505  EA
01335'042523  SE
01336'052040   T
01337'046511  IM
01340'020105  E
01341'052123  ST
01342'050105  EP
01343'000000  *
01344'047101  DMS10:   .TXT     *AN
01345'020131  Y
01346'052117  OT
01347'042510  HE
01350'020122  R
01351'042513  KE
01352'020131  Y
01353'020055  -
01354'047516  NO
01355'041440   C
01356'040510  HA
01357'043516  NG
01360'00010   E*
01361'042516  DMS11:   .TXT     *NE
01362'020127  W
01363'040526  VA
01364'052514  LU
01365'051505  ES
01366'000000  *
01367'054524  DM10:    .TXT     *TY
01370'042520  PE
01371'053440   W
```

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```
01372'052040   T
01373'020117  O
01374'047515  MO
01375'044504  DI
01376'054506  FY
01377'053440   W
01400'044505  EI
01401'044107  GH
01402'051524  TS
01403'000000  *
01404'020040  MW1:     .TXT     *
01405'047524  TO
01406'020117  O
01407'042510  HE
01410'053101  AV
01411'000131  Y*
01412'025040  MW2:     .TXT     " *
01413'025052  **
01414'025052  **
01415'025052  **
01416'025052  **
01417'025052  **
01420'000000  "
                       .END
```

```
                        .TITL   UPDAT
                        .ENT    .ALLB,.SING,.CPNT
                        .EXTD   .M1,.M2,.M3,.M4,.M5,.M6,.M7,.MSKR
                        .EXTD   .PUN1,.PON2,.PRN1,.EMPT,.PSIZ,.LENG
                        .EXTD   .TYP
                        .EXTD   .MEM
                        .ZREL
00000-000000' .ALLB:    ALLB
00001-000053' .SING:    SING
00002-000504' .CPNT:    CHA     ;POINTER TO WORD THAT CAN BE MODIFIED
00003-000000  XA:       0
00004-000000  YA:       0
00005-000000  COS:      0
00006-000000  SIN:      0
00007-000000  COSF:     0
00010-000000  SINF:     0
00011-000000  NB:       0
00012-000000  NP:       0
00013-000000  NPNB:     0
00014-000000  L:        0
                        .NREL
              ;ROUTINE TO UPDATE ALL BLOCK CONTACTS
              ;         JSR @.ALLB
              ;
00000'054416  ALLB:     STA     3,ALL3
00001'034001$           LDA     3,.M1
00002'102400            SUB     0,0
00003'040414            STA     0,NBB
              ;BLOCK SCAN------------
00004'054414  BEGIN:    STA     3,HOLD
00005'031400            LDA     2,0,3
00006'151005            MOV     2,2,SNR
00007'002407            JMP     @ALL3    ;NO MORE BLOCKS. EXIT!
00010'024407            LDA     1,NBB
00011'004442            JSR     SING     ;UPDATE SINGLE BLOCK CONTACTS
00012'010405            ISZ     NBB
00013'034405            LDA     3,HOLD
00014'175400            INC     3,3
00015'000767            JMP     BEGIN
00016'000000  ALL3:     0
00017'000000  NBB:      0
00020'000000  HOLD:     0
              ;
              ;AFTER ALL SIDES HAVE BEEN SCANNED, THIS
              ;ROUTINE THROWS OUT ALL ENTRIES IN CONTACT
              ;LIST THAT HAVE NOT BEEN FLAGGED.
00021'024506  SCAN:     LDA     1,LBIT   ;"PRESERVE" FLAG
00022'034005$           LDA     3,.M5
00023'020011-           LDA     0,NB
00024'117000            ADD     0,3      ;LOCATOR OF CONTACT LIST
00025'054425            STA     3,OLINK  ;BACKWARDS LINK
00026'035400            LDA     3,0,3    ;GET POINTER (OR -1)
00027'175112  PHONE:    MOVL#   3,3,SZC  ;END?
00030'002500            JMP     @SIN3    ;DONE. EXIT!
00031'021400            LDA     0,0,3    ;1ST WORD
00032'123415            AND#    1,0,SNR  ;IS PRESERVE FLAG SET
00033'000410            JMP     DELET    ;NO, DELETE ENTRY
00034'122400            SUB     1,0      ;KEEP ENTRY; REMOVE FLAG
00035'041400            STA     0,0,3    ;PUT IT BACK
00036'171400            INC     3,2
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00037'151400            INC     2,2      ;GET ACTUAL LINK ADDRESS
00040'050412            STA     2,OLINK ;REMEMBER REVERSE LINK
00041'035402            LDA     3,2,3    ;GET NEXT ENTRY
00042'000765            JMP     PHONE
               ;TO DELETE AN ENTRY, AND PUT IT IN THE
               ;"EMPTY" LIST.
00043'020014S  DELET:   LDA     0,.EMPT ;GET LINK FROM LOCATOR
00044'054014S           STA     3,.EMPT ;PUT IN NEW LINK
00045'031402            LDA     2,2,3    ;OLD LINK FIELD OF ENTRY
00046'041402            STA     0,2,3    ;STORE EMPT LINK IN IT
00047'052403            STA     2,@OLINK        ;BYPASS DELETED
00050'155000            MOV     2,3      ;NEXT ENTRY
00051'000756            JMP     PHONE           ;  ENTRY
00052'000000   OLINK:   0
               ;
               ;ROUTINE TO UPDATE SINGLE BLOCK CONTACTS
               ;        JSR @.SING
               ;
               ;INPUT: AC1 - BLOCK #
               ;        AC2 - POINTER TO START OF DATA, BLOCK NB
               ;
00053'054455   SING:    STA     3,SIN3
00054'044011-           STA     1,NB
00055'021014            LDA     0,14,2
00056'101005            MOV     0,0,SNR
00057'002451            JMP     @SIN3    ;ZERO AREA. EXIT!
00060'021000            LDA     0,0,2    ;CONTROL WORD
00061'024010S           LDA     1,.MSKR
00062'107400            AND     0,1      ;NO. OF POINTS
00063'044446            STA     1,NPNTS ;NEGATIVE POINT COUNTER
00064'126400            SUB     1,1
00065'044012-           STA     1,NP
00066'006016S           JSR     @.LENG   ;GET LENGTH L THIS SIDE
00067'040014-           STA     0,L
00070'006011S           JSR     @.PON1   ;GET GLOBAL CO-ORDS
00071'040441            STA     0,X0
00072'044441            STA     1,Y0
00073'040003-           STA     0,XA
00074'044004-           STA     1,YA
00075'024012-           LDA     1,NP
00076'000420            JMP     DOWN
00077'125400   BACK:    INC     1,1
00100'006011S           JSR     @.PON1
00101'040573            STA     0,XB
00102'044573            STA     1,YB
00103'050423            STA     2,AC2
00104'004433            JSR     RED      ;SEARCH FOR CONTACTS
00105'030421            LDA     2,AC2
00106'010012-           ISZ     NP
00107'024012-           LDA     1,NP
00110'006016S           JSR     @.LENG
00111'040014-           STA     0,L
00112'020562            LDA     0,XB     ;NEW BECOMES OLD
00113'040003-           STA     0,XA
00114'020561            LDA     0,YB
00115'040004-           STA     0,YA
00116'014413   DOWN:    DSZ     NPNTS    ;JUMP OUT IF DONE
00117'000760            JMP     BACK
00120'020412            LDA     0,X0     ;LAST LINE
00121'040553            STA     0,XB
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00122'020411           LDA      0,Y0
00123'040552           STA      0,YB
00124'004413           JSR      RED       ;SEARCH FOR CONTACTS
00125'000674           JMP      SCAN      ;SCAN FOR FLAGS
00126'000000  AC2:     0
00127'020000  LBIT:    20000
00130'000000  SIN3:    0
00131'000000  NPNTS:   0
00132'000000  X0:      0
00133'000000  Y0:      0
00134'000000  XLBOX:   0
00135'000000  YLBOX:   0
00136'000000  XUBOX:   0
              ;FIND RANGE OF BOX SCAN (XRANG,YRANG)
              ;FOR LINE [(XA,YA),(XB,YB)]
00137'054543  RED:     STA      3,SVR3
00140'102520           SUBZL    0,0
00141'040552           STA      0,BYPAS ;INITIALIZE SKIP FLAG
00142'030547           LDA      2,C100
00143'020004-          LDA      0,YA
00144'024531           LDA      1,YB
00145'122512           SUBL#    1,0,SZC ;IS YA>=YB?
00146'000404           JMP      REV       ;NO
00147'044530           STA      1,YL      ;STORE YB AS LOWER
00150'040531           STA      0,YU      ;YA AS UPPER
00151'000403           JMP      ON
00152'040525  REV:     STA      0,YL      ;THE REVERSE
00153'044526           STA      1,YU
00154'020003-  ON:     LDA      0,XA
00155'024517           LDA      1,XB
00156'122512           SUBL#    1,0,SZC ;DO SAME FOR X
00157'000404           JMP      VER
00160'044516           STA      1,XL
00161'040517           STA      0,XU
00162'000403           JMP      ONN
00163'040513  VER:     STA      0,XL
00164'044514           STA      1,XU
              ;FIND BOX ADDRESSES
00165'024511  ONN:     LDA      1,XL
00166'102400           SUB      0,0
00167'073101           DIV
00170'101004           MOV      0,0,SZR
00171'000405           JMP      .+5
00172'125005           MOV      1,1,SNR
00173'000403           JMP      .+3
00174'102520           SUBZL    0,0
00175'106400           SUB      0,1
00176'044736           STA      1,XLBOX ;NO. X BOXES FROM ORIG
00177'024500           LDA      1,YL
00200'102400           SUB      0,0
00201'073101           DIV
00202'101004           MOV      0,0,SZR
00203'000405           JMP      .+5
00204'125005           MOV      1,1,SNR
00205'000403           JMP      .+3
00206'102520           SUBZL    0,0
00207'106400           SUB      0,1
00210'044725           STA      1,YLBOX ;NO. Y BOXES FROM
00211'024467           LDA      1,XU
00212'102400           SUB      0,0
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00213'073101          DIV
00214'044722          STA     1,XUBOX ;NO. X BOXES FROM
00215'024464          LDA     1,YU    ;ORIGIN TO END
00216'102400          SUB     0,0
00217'073101          DIV
00220'020715          LDA     0,YLBOX ;NO. Y BOXES....
00221'106400          SUB     0,1     ;NO. Y BOXES IN SCAN
00222'124000          COM     1,1
00223'044463          STA     1,YRANG ;ADD 1, MAKE -VE
00224'034003S         LDA     3,.M3
00225'103120          ADDZL   0,0     ;MULTIPLY YLBOX BY 20
00226'103120          ADDZL   0,0
00227'117000          ADD     0,3
00230'024706          LDA     1,XUBOX
00231'020703          LDA     0,XLBOX
00232'106400          SUB     0,1     ;NO.X BOXES IN SCAN
00233'124000          COM     1,1
00234'044451          STA     1,XRANG
00235'044452          STA     1,XCNT  ;COPY FOR SCAN ROUTINE
00236'117000          ADD     0,3     ;START BOX ADDR IN AC3
00237'054445  LOOPO:  STA     3,NLEFT ;LEFT-HAND POINTER
00240'054443  LOOP:   STA     3,KEEP  ;MOVING X POINTER
00241'035400          LDA     3,0,3
00242'175112          MOVL#   3,3,SZC ;END MARK?
00243'000415          JMP     ENDM    ;YES
00244'021400  THERE:  LDA     0,0,3   ;GET WORD IN LINKED LIST
00245'030010S         LDA     2,.MSKR
00246'113400          AND     0,2     ;JUST NB IN AC2
00247'024011-         LDA     1,NB
00250'132415          SUB#    1,2,SNR
00251'000404          JMP     MOVE    ;SAME BLOCK! DISCARD!
00252'054440          STA     3,SV3
              ;
00253'004443          JSR     PUSH    ;(NP:NB) IN AC0; HOME NB IN AC1
              ;
00254'034436          LDA     3,SV3
00255'035401  MOVE:   LDA     3,1,3   ;2ND WORD (=LINK)
00256'175113          MOVL#   3,3,SNC ;END OF LINK CHAIN?
00257'000765          JMP     THERE
00260'034423  ENDM:   LDA     3,KEEP
00261'175400          INC     3,3     ;STEP POINTER IN X DIREC.
00262'010425          ISZ     XCNT    ;END OF X SCAN?
00263'000755          JMP     LOOP    ;NO
00264'020421          LDA     0,XRANG ;YES, GET OLD -VE X COUNT
00265'040422          STA     0,XCNT
00266'020422          LDA     0,SIXTN
00267'034415          LDA     3,NLEFT
00270'117000          ADD     0,3     ;1 ROW UP, L.H. SIDE
00271'010415          ISZ     YRANG   ;END OF Y SCAN?
00272'000745          JMP     LOOPO   ;NO
00273'002407          JMP     @SVR3   ;YES, EXIT!
00274'000000  XB:     0
00275'000000  YB:     0
00276'000000  XL:     0
00277'000000  YL:     0
00300'000000  XU:     0
00301'000000  YU:     0
00302'000000  SVR3:   0
00303'000000  KEEP:   0
00304'000000  NLEFT:  0
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00305'000000  XRANG:   0
00306'000000  YRANG:   0
00307'000000  XCNT:    0
00310'000020  SIXTN:   20
00311'000100  C100:    100
00312'000000  SV3:     0
00313'000000  BYPAS:   0
00314'000525' SVP3R:   SVP3
00315'000630' YTGR:    YTGET
00316'056776  PUSH:    STA     3,@SVP3R
00317'040013-          STA     0,NPNB
00320'014773           DSZ     BYPAS    ;ONLY COMPUTE COS & SIN
00321'000434           JMP     JELLO    ;  FIRST TIME ROUND
              ;TO GET LOCAL COS AND SIN OF THIS EDGE
00322'020752           LDA     0,XB
00323'024003-          LDA     1,XA
00324'122400           SUB     1,0      ;XB-XA
00325'040007-          STA     0,COSF   ;COS SIGN FLAG
00326'101112           MOVL#   0,0,SZC ;-VE?
00327'100400           NEG     0,0      ;YES, GET ABS(XB-XA)
00330'030014-          LDA     2,L      ;LENGTH OF EDGE
00331'126400           SUB     1,1
00332'142513           SUBL#   2,0,SNC ;XD>=L?
00333'124001           COM     1,1,SKP ;SET AC1 TO 1111...
00334'073101           DIV
00335'101112           MOVL#   0,0,SZC ;ROUND UP IF NECESSARY
00336'125400           INC     1,1
00337'044005-          STA     1,COS
00340'020735           LDA     0,YB
00341'024004-          LDA     1,YA
00342'122400           SUB     1,0      ;YB-YA
00343'040010-          STA     0,SINF   ;SIN SIGN FLAG
00344'101112           MOVL#   0,0,SZC ;-VE?
00345'100400           NEG     0,0
00346'126400           SUB     1,1
00347'142513           SUBL#   2,0,SNC ;YD>=L?
00350'124001           COM     1,1,SKP ;YES
00351'073101           DIV
00352'101112           MOVL#   0,0,SZC
00353'125400           INC     1,1      ;ROUND UP
00354'044006-          STA     1,SIN
              ;
              ;GET TRANSFORMED CO-ORDS OF X,Y
              ;COMPUTES: XT=XG*COS(A)+YG*SIN(A)
              ;          YT=YG*COS(A)-XG*SIN(A)
              ;
00355'020013- JELLO:   LDA     0,NPNB   ;(NP:NB)
00356'024010$          LDA     1,.MSKR
00357'115300           MOVS    0,3
00360'123400           AND     1,0      ;NB IN AC0
00361'167400           AND     3,1      ;NP IN AC1
00362'044535           STA     1,OTHER
00363'034001$          LDA     3,.M1
00364'117000           ADD     0,3
00365'031400           LDA     2,0,3    ;POINTER TO NEW BLOCK
00366'006011$          JSR     @.PON1   ;GET GLOBAL CO-ORDS
00367'040537           STA     0,X
00370'044537           STA     1,Y      ;ACTUAL CONTACT CO-ORDS
00371'034003-          LDA     3,XA
00372'162400           SUB     3,0
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00373'040522          STA     0,XG      ;REL. TO EDGE START
00374'034004-         LDA     3,YA
00375'166400          SUB     3,1
00376'044520          STA     1,YG
               ;
00377'006716          JSR     @YTGR
00400'054524          STA     3,YT      ;LOCAL, TRANSFORMED Y
00401'126520          SUBZL   1,1
00402'166512          SUBL#   3,1,SZC ;IS YT>1?
00403'002522          JMP      SVP3     ;YES. NOT TOUCHING. EXIT!
00404'024517          LDA       TWO
00405'137112          ADDL#   1,3,SZC ;IS YT<=-3?
00406'002517          JMP     @SVP3     ;YES. TOO DEEP. EXIT!
               ;
00407'030006-         LDA     2,SIN     ;NOW FOR XT
00410'024506          LDA     1,YG
00411'102440          SUBO    0,0
00412'125112          MOVL#   1,1,SZC ;SET CARRY IF NEG
00413'124440          NEGO    1,1       ;AND MAKE AC1 +VE
00414'073301          MUL
00415'125112          MOVL#   1,1,SZC
00416'101400          INC     0,0       ;ROUND UP
00417'101002          MOV     0,0,SZC ;CARRY?
00420'100400          NEG     0,0       ;RESTORE SIGN
00421'024010-         LDA     1,SINF
00422'125102          MOVL    1,1,SZC ;SIGN OF SIN
00423'100400          NEG     0,0
00424'115000          MOV     0,3       ;SHUNT INTO AC3
00425'024470          LDA     1,XG
00426'030005-         LDA     2,COS
00427'102440          SUBO    0,0
00430'125112          MOVL#   1,1,SZC
00431'124440          NEGO    1,1
00432'073301          MUL
00433'125112          MOVL#   1,1,SZC
00434'101400          INC     0,0
00435'101002          MOV     0,0,SZC
00436'100400          NEG     0,0
00437'024007-         LDA     1,COSF
00440'125102          MOVL    1,1,SZC
00441'100400          NEG     0,0
00442'117000          ADD     0,3       ;ADD TO PREVIOUS RESULT
               ;LOCAL, TRANSFORMED X NOW IN AC3
               ;
00443'024014-         LDA     1,L
00444'166512          SUBL#   3,1,SZC ;IS XT>L?
00445'002460          JMP     @SVP3     ;YES
00446'175112          MOVL#   3,3,SZC ;IS XT<0?
00447'002456          JMP     @SVP3     ;YES
               ;TO FIND IF THIS CONTACT ALREADY EXISTS
00450'034005S         LDA     3,.MS
00451'020011-         LDA     0,NB
00452'117000          ADD     0,3
00453'054445          STA     3,PRODL ;REMEMBER CONTACT LOCATOR
00454'024012-         LDA     1,NP
00455'035400          LDA     3,0,3     ;GET POINTER (OR -1)
00456'175112   SEA:   MOVL#   3,3,SZC
00457'000430          JMP     CLOUD     ;THIS CONTACT NOT STORED
00460'021400          LDA     0,0,3     ;1ST WORD CONTACT LIST
00461'030010S         LDA     2,.MSKR
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00462'113400            AND     0,2     ;POINT (EDGE) NUMBER
00463'132414            SUB#    1,2,SZR ;SAME EDGE?
00464'000405            JMP     WAVES   ;NO
00465'021401            LDA     0,1,3   ;GET POINT,BLOCK
00466'030013-           LDA     2,NPNB ;COMPOSITE WORD
00467'112415            SUB#    0,2,SNR ;SAME?
                ;--ALREADY TOUCHING---
00470'000403            JMP     REN     ;YES. UPDATE SIN, COS ETC.
00471'035402    WAVES:  LDA     3,2,3   ;NO. GET LINK FIELD
00472'000764            JMP     SEA
                ;ADD IN EXTRA NORMAL FORCE TO PREVENT PUNCH-THROUGH
                ;IF YT < -2
00473'024431    REN:    LDA     1,YT
00474'125503            INCL    1,1,SNC
00475'000466    CHANGE: JMP     RENEW   ;THIS WORD CAN BE REPLACED
00476'020405            LDA     0,FORCE
00477'025406            LDA     1,6,3   ;NORMAL FORCE, FN
00500'107000            ADD     0,1     ;ADD IN INCREMENT
00501'045406            STA     1,6,3   ;PUT FN BACK
00502'000773            JMP     CHANGE
00503'010000    FORCE:  10000           ;PREVENTIVE FORCE
00504'000475'   CHA:    CHANGE
00505'000466            JMP     RENEW-CHANGE,1
00506'000454            JMP     HEAD-CHANGE,1
                ;
                ;--NOT ALREADY TOUCHING---
00507'024415    CLOUD:  LDA     1,YT
00510'125004            MOV     1,1,SZR ;THROW OUT IF
00511'125112            MOVL#   1,1,SZC ;   YT>0
00512'000554            JMP     WEED
00513'002412            JMP     @SVP3
00514'020000    FLAG:   20000
00515'000000    XG:     0
00516'000000    YG:     0
00517'000000    OTHER:  0       ;CONTACT POINT #
00520'000000    PRODL:  0
00521'100000    SFLAG:  100000
00522'040000    CFLAG:  40000
00523'000002    TWO:    2
00524'000000    YT:     0
00525'000000    SVP3:   0
00526'000000    X:      0       ;ACTUAL CONTACT CO-ORDS
00527'000000    Y:      0
00530'000126'   AC2R:   AC2
00531'000000    AC3S:   0
                ;
                ;TO INSERT NEW ENTRY....
                ;
00532'034014S   ENTER:  LDA     3,.EMPT ;GET ADDR. IN EMPT. LOC.
00533'175112            MOVL#   3,3,SZC ;IS IT -1?
00534'000460            JMP     FLOC    ;YES. MUST USE MORE CORE
00535'031402            LDA     2,2,3   ;GET LINK IN FREE SPACE
00536'050014S           STA     2,.EMPT ;UPDATE EMPTY LOCATOR
00537'030761    FROG:   LDA     2,PRODL ;GET CONTACT LOCATOR
00540'021000            LDA     0,0,2
00541'055000            STA     3,0,2   ;STORE NEW ADDR. IN IT
00542'041402            STA     0,2,3   ;PUT IN NEW LINK FIELD
                ;NOW PUT IN REST OF DATA
00543'102400            SUB     0,0     ;SET ZERO IN FOLLOWING:
00544'041403            STA     0,3,3   ; S (SHEAR DISP)
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00545'041404          STA    0,4,3    ;SDEL (INCR. S.D.)
00546'041405          STA    0,5,3    ;NDEL (INCR. N.D.)
00547'041406          STA    0,6,3    ; FN (NORMAL FORCE)
00550'041407          STA    0,7,3    ; FS (SHEAR FORCE)
00551'054760  HEAD:   STA    3,AC3S
00552'024012-         LDA    1,NP
00553'032755          LDA    2,@AC2R
00554'006017S         JSR    @.TYP
00555'101300          MOVS   0,0
00556'107000          ADD    0,1
00557'034752          LDA    3,AC3S
00560'045400          STA    1,0,3    ;HEAD OF LIST
00561'020013-         LDA    0,NPNB
00562'041401          STA    0,1,3    ;2ND WORD
00563'020743  RENEW:  LDA    0,X
00564'041412          STA    0,12,3   ;GLOBAL X OF CONTACT
00565'020742          LDA    0,Y
00566'041413          STA    0,13,3   ;GLOBAL Y OF CONTACT
00567'020006-         LDA    0,SIN
00570'041410          STA    0,10,3   ;SIN
00571'020005-         LDA    0,COS
00572'041411          STA    0,11,3   ;COS
00573'020721          LDA    0,FLAG   ;"PRESERVE" FLAG
00574'030010-         LDA    2,SINF
00575'151113          MOVL#  2,2,SNC
00576'000403          JMP    .+3
00577'024722          LDA    1,SFLAG
00600'123000          ADD    1,0      ;ADD IN SIN FLAG IF -VE
00601'030007-         LDA    2,COSF
00602'151113          MOVL#  2,2,SNC
00603'000403          JMP    .+3
00604'024716          LDA    1,CFLAG
00605'123000          ADD    1,0      ;ADD IN COS FLAG IF -VE
00606'025400          LDA    1,0,3    ;OLD HEAD
00607'030420          LDA    2,SCMSK
00610'147400          AND    2,1
00611'107000          ADD    0,1
00612'045400          STA    1,0,3    ;NEW HEAD
00613'002712          JMP    @SVP3
00614'034007S FLOC:   LDA    3,.M7    ;NEXT FREE LOCATION
00615'020020S         LDA    0,.MEM   ;MAX. ADDRESS POSSIBLE
00616'024015S         LDA    1,.PSIZ
00617'167000          ADD    3,1
00620'122513          SUBL#  1,0,SNC ;STORAGE OVERFLOW?
00621'000404          JMP    NOG      ;NO, OK
00622'006013S         JSR    @.PRN1   ;YES. RING THE BELL
00623'000007          7
00624'002701          JMP    @SVP3    ;EXIT WITHOUT STORING
00625'044007S NOG:    STA    1,.M7    ;UPDATE FREE POINTER
00626'000711          JMP    FROG
00627'017777  SCMSK:  17777  ;TO MASK OFF OLD S,C,P FLAGS
              ;
              ;TO CALCULATE YT
              ; INPUT:  YG IN AC1
00630'054435  YTGET:  STA    3,YTSAV
00631'030005-         LDA    2,COS
00632'102440          SUBO   0,0
00633'125112          MOVL#  1,1,SZC
00634'124440          NEGO   1,1
00635'073301          MUL
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00636'125112            MOVL#    1,1,SZC
00637'101400            INC      0,0
00640'101002            MOV      0,0,SZC
00641'100400            NEG      0,0
00642'024007-           LDA      1,COSF
00643'125102            MOVL     1,1,SZC
00644'100400            NEG      0,0
00645'115000            MOV      0,3      ;PARTIAL SUM IN AC3
00646'024647            LDA      1,XG
00647'030006-           LDA      2,SIN
00650'102440            SUBO     0,0
00651'125112            MOVL#    1,1,SZC
00652'124440            NEGO     1,1
00653'073301            MUL
00654'125112            MOVL#    1,1,SZC
00655'101400            INC      0,0
00656'101002            MOV      0,0,SZC
00657'100400            NEG      0,0
00660'024010-           LDA      1,SINF
00661'125102            MOVL     1,1,SZC
00662'100400            NEG      0,0
00663'116400            SUB      0,3      ;SUBTRACT FROM PREVIOUS RESULT
00664'002401            JMP      @YTSAV
00665'000000  YTSAV:    0
00666'024631  WEED:     LDA      1,OTHER ;CONTACT CANDIDATE
              ;ROUTINE TO WEED OUT IMPOSSIBLE CONTACTS
00667'044444            STA      1,SWIT
00670'125005            MOV      1,1,SNR ;ZERO?
00671'000404            JMP      TOAD     ;YES
00672'102520            SUBZL    0,0
00673'106400            SUB      0,1      ;TRY [POINT-1]
00674'000402            JMP      GETIT
00675'126520  TOAD:     SUBZL    1,1      ;TRY POINT #1
00676'006012S GETIT:    JSR      @.PON2  ;(PONT ALREADY PRIMED)
00677'050435            STA      2,SV2
00700'034003-           LDA      3,XA
00701'162400            SUB      3,0
00702'040613            STA      0,XG     ;REL X
00703'034004-           LDA      3,YA
00704'166400            SUB      3,1      ;REL Y
00705'004723            JSR      YTGET
00706'024615            LDA      1,TWO
00707'167112            ADDL#    3,1,SZC ;YT1<=-2?
00710'002615            JMP      @SVP3    ;YES. IMPOSSIBLE CONTACT
00711'020422            LDA      0,SWIT
00712'101112            MOVL#    0,0,SZC ;2ND TIME ROUND
00713'000617            JMP      ENTER    ;YES. STORE THE CONTCT
00714'030420            LDA      2,SV2
00715'025000            LDA      1,0,2    ;CONTROL WORD
00716'034010S           LDA      3,.MSKR
00717'167400            AND      3,1      ;NO. OF POINTS (PMAX)
00720'176000            ADC      3,3      ;-1
00721'054412            STA      3,SWIT   ;SET FOR EXIT 2ND TIME
00722'101004            MOV      0,0,SZR
00723'000403            JMP      NEWT     ;SWIT MUST BE >0
00724'167000            ADD      3,1      ;TRY POINT (PMAX-1)
00725'000751            JMP      GETIT
00726'101400  NEWT:     INC      0,0      ;OTHER +1
00727'106415            SUB#     0,1,SNR ;IS IT EQUAL TO PMAX?
00730'102400            SUB      0,0      ;YES. USE POINT #0
```

```
00731'105000              MOV     0,1
00732'000744              JMP     GETIT
00733'000000  SWIT:       0
00734'000000  SV2:        0
                          .END
```

```
                        .TITL   REBOX
                ;TO RE-CLASSIFY (IF NECESSARY) ALL
                ;THE POINTS OF ONE BLOCK IN NEW
                ;BOXES.
                ;
                ;       JSR @.REBX
                ;   (INPUT: AC2 - POINTER TO BLOCK DATA,
                ;           AC1 - POINTER TO LOCATOR )
                ;AC2 IS PRESERVED.
                        .ENT    PUP      ;TEMP TEST ENTRY
                        .ENT    .REBX,.REBZ,.MSKR
                        .EXTD   .M1,.M3,.M4,.PON1,.PON2,.PRES,.LENG
                        .ZREL
00000-000000' .REBX:    REBX
00001-000002' .REBZ:    REBZ     ;ENTRY WITH NB IN AC1
00002-000377  .MSKR:    377
                        .NREL
00000'020001S REBX:     LDA     0,.M1
00001'106400            SUB     0,1
00002'044506  REBZ:     STA     1,NB     ;REGENERATE NB
00003'054477            STA     3,SVRB3
00004'050475            STA     2,SV2
00005'021000            LDA     0,0,2
00006'024002-           LDA     1,.MSKR
00007'123400            AND     1,0
00010'040504            STA     0,PCNT
00011'126400            SUB     1,1
00012'044475            STA     1,NP
00013'006004S           JSR     @.PON1
00014'000403            JMP     PLACE
00015'024472  COW:      LDA     1,NP
00016'006005S           JSR     @.PON2
00017'176520  PLACE:    SUBZL   3,3      ;CHECK IF ON SCREEN
00020'162512            SUBL#   3,0,SZC ;X<=0?
00021'000523            JMP     FIX      ;YES, FIX THE BLOCK
00022'166512            SUBL#   3,1,SZC ;Y<=0?
00023'000521            JMP     FIX
00024'034466            LDA     3,C1777
00025'162513            SUBL#   3,0,SNC ;X>=1023 (DECIMAL)?
00026'000516            JMP     FIX
00027'034464            LDA     3,C1414
00030'166513            SUBL#   3,1,SNC ;Y>=780 (DEC)?
00031'000513            JMP     FIX
00032'044453            STA     1,NY
                ;
00033'105000  CONT:     MOV     0,1      ;FIND NEW BOX
00034'034002S           LDA     3,.M3
00035'030447            LDA     2,C100
00036'102400            SUB     0,0
00037'073101            DIV
00040'137000            ADD     1,3
00041'102400            SUB     0,0
00042'024443            LDA     1,NY
00043'073101            DIV
00044'127120            ADDZL   1,1
00045'127120            ADDZL   1,1
00046'137000            ADD     1,3      ;BOX ADDR. IN AC3
00047'054442            STA     3,BOX
00050'171000            MOV     3,2
00051'020437            LDA     0,NB
```

```
00052'024435         LDA     1,NP
00053'125300         MOVS    1,1
00054'123000         ADD     1,0      ;(NP:NB) IN AC0
00055'004502         JSR     FIND     ;FIND OLD BOX
00056'000461         JMP     ITER     ;SUCCESS! NO CHANGE
00057'034437         LDA     3,LIST   ;FAILURE! MUST SEARCH AROUND
00060'054426  WINE:  STA     3,POINT
00061'030430         LDA     2,BOX
00062'025400         LDA     1,0,3
00063'125005         MOV     1,1,SNR
00064'000453         JMP     ITER     ;WHERE IS IT
00065'133000         ADD     1,2
00066'024002$        LDA     1,.M3
00067'132512         SUBL#   1,2,SEC
00070'000406         JMP     NEXT     ;NON-EXISTENT BOX
00071'024003$        LDA     1,.M4
00072'132513         SUBL#   1,2,SNC
00073'000403         JMP     NEXT     ;  DITTO
00074'004463         JSR     FIND     ;TRY THIS BOX
00075'000433         JMP     FOUND    ;FOUND IT!
00076'034410  NEXT:  LDA     3,POINT  ;NO GOOD. TRY NEXT BOX
00077'175400         INC     3,3
00100'000760         JMP     WINE
00101'000000  SV2:   0
00102'000000  SVRB3: 0
00103'000000  OLD:   0
00104'000100  C100:  100
00105'000000  NY:    0
00106'000000  POINT: 0
00107'000000  NP:    0
00110'000000  NB:    0
00111'000000  BOX:   0
00112'001777  C1777: 1777
00113'001414  C1414: 1414
00114'000000  PCNT:  0
00115'004000  FBIT:  4000    ;MASTER FIX BIT (OVERRIDES MAN. BIT)
00116'000117' LIST:  .+1
              ;LIST OF SURROUNDING BOXES, IN EXPECTED
              ;ORDER OF PROBABLE OCCURANCE
00117'000020         20
00120'177777         -1
00121'000001         1
00122'177760         -20
00123'000017         17
00124'000021         21
00125'177757         -21
00126'177761         -17
00127'000000         0
00130'034753  FOUND: LDA     3,OLD    ;GET CALLING ADDR
00131'025001         LDA     1,1,2    ;EXISTING LINK
00132'045400         STA     1,0,3    ;BRIDGE ACROSS ENTRY
00133'034756         LDA     3,BOX    ;NEW BOX ADDRESS
00134'021400         LDA     0,0,3    ;POINTER (OR -1)
00135'051400         STA     2,0,3    ;PUT IN NEW ADDRESS
00136'041001         STA     0,1,2    ;COMPLETE LINK
00137'010750  ITER:  ISZ     NP       ;NEXT POINT
00140'014754         DSZ     PCNT
00141'000654         JMP     COW      ;NEXT POINT IF NOT DONE
00142'030737         LDA     2,SV2
00143'000430         JMP     PUP      ;UPDATE ANY PRESS. SEGS
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00144'044741  FIX:    STA     1,NY
00145'025000          LDA     1,0,2
00146'034747          LDA     3,FBIT
00147'167415          AND#    3,1,SNR ;SKIP IF FLAG ALREADY SET
00150'167000          ADD     3,1     ;ADD IN MASTER FIX FLAG
00151'045000          STA     1,0,2   ;PUT CONTROL WORD BACK
00152'176400          SUB     3,3     ;ALLOW "INVISIBLE"
00153'055020          STA     3,20,2  ;BLOCKS
00154'055021          STA     3,21,2  ;  TO
00155'055022          STA     3,22,2  ;INTERACT
00156'000655          JMP     CONT    ;KEEP GOING
              ;ROUTINE TO FOLLOW CHAIN TO FIND (NP:NB)
00157'050724  FIND:   STA     2,OLD   ;CALLING ADDR
00160'031000          LDA     2,0,2   ;ADDR OF 1ST WORD
00161'000407          JMP     MID
00162'025000  ROUND:  LDA     1,0,2
00163'106415          SUB#    0,1,SNR ;COMPARE
00164'001400          JMP     0,3     ;SUCCESS! ADDR. IN AC2
00165'145400          INC     2,1
00166'044715          STA     1,OLD   ;OLD LINK ADDR.
00167'031001          LDA     2,1,2   ;GET LINK
00170'151112  MID:    MOVL#   2,2,SEC ;END OF CHAIN?
00171'001401          JMP     1,3     ;YES. FAILURE EXIT
00172'000770          JMP     ROUND
              ;
              ;ROUTINE TO UPDATE FX, FY IN ANY
              ;PRESSURE SEGMENT FOR BLOCK NB
              ;
00173'021000  PUP:    LDA     0,0,2
00174'024506          LDA     1,PMSK
00175'123415          AND#    1,0,SNR ;QUICK CHECK FOR PRESS.
00176'002704          JMP     @SVRB3  ;NONE FOR THIS BLOCK
00177'030006S         LDA     2,.PRES
00200'034710  GRAPE:  LDA     3,NB
00201'151113  PLUM:   MOVL#   2,2,SNC
00202'000403          JMP     .+3
00203'030676          LDA     2,SV2
00204'002676          JMP     @SVRB3  ;END OF PR. SEG. LIST
00205'025000          LDA     1,0,2   ;NPNB THIS SEG.
00206'020002-         LDA     0,.MSKR
00207'123400          AND     1,0     ;NB1 (BLOCK #)
00210'116415          SUB#    0,3,SNR ;SAME BLOCK?
00211'000403          JMP     PRUNE   ;YES; UPDATE FX,FY
00212'031002          LDA     2,2,2   ;NO, GET NEXT LINK
00213'000766          JMP     PLUM
00214'106700  PRUNE:  SUBS    0,1     ;NP1 (EDGE #)
00215'050466          STA     2,PR2   ;CURRENT PR. LIST POINTER
00216'035001          LDA     3,1,2   ;FORCE
00217'054465          STA     3,FORCE
00220'044465          STA     1,NPREM ;REMEMBER 1ST CORNER
00221'034001S         LDA     3,.M1
00222'117000          ADD     0,3
00223'031400          LDA     2,0,3   ;BLOCK POINTER
00224'006007S         JSR     @.LENG  ;GET LENGTH
00225'040461          STA     0,L
00226'006004S         JSR     @.PON1
00227'040460          STA     0,XA
00230'044460          STA     1,YA
00231'024454          LDA     1,NPREM
00232'125400          INC     1,1
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00233'021000        LDA     0,0,2
00234'034002-       LDA     3,.MSKR
00235'163400        AND     3,0      ;NC
00236'106415        SUB#    0,1,SNR ;CHECK FOR LAST CORNER
00237'126400        SUB     1,1
00240'006005S       JSR     @.PON2
00241'030446        LDA     2,XA
00242'112400        SUB     0,2      ;(XA-XB)
00243'155000        MOV     2,3      ;SAVE FOR SIGN
00244'044445        STA     1,YB
00245'024437        LDA     1,FORCE
00246'102440        SUBO    0,0
00247'151112        MOVL#   2,2,SZC ;CHECK SIGN
00250'150400        NEG     2,2
00251'073301        MUL
00252'030434        LDA     2,L
00253'073101        DIV
00254'175112        MOVL#   3,3,SZC ;RESTORE SIGN
00255'124400        NEG     1,1
00256'044434        STA     1,FY
00257'030432        LDA     2,YB
00260'020430        LDA     0,YA
00261'112400        SUB     0,2      ;(YB-YA)
00262'155000        MOV     2,3
00263'024421        LDA     1,FORCE
00264'102440        SUBO    0,0
00265'151112        MOVL#   2,2,SZC
00266'150400        NEG     2,2
00267'073301        MUL
00270'030416        LDA     2,L
00271'073101        DIV              ;(YB-YA)*F/L
00272'175112        MOVL#   3,3,SZC
00273'124400        NEG     1,1      ;FX
00274'030407        LDA     2,PR2
00275'045004        STA     1,4,2    ;STORE FX IN LIST
00276'024414        LDA     1,FY
00277'045005        STA     1,5,2    ;FY IN LIST
00300'031002        LDA     2,2,2    ;LINK
00301'000677        JMP     GRAPE
00302'000400 PMSK:  400
00303'000000 PR2:   0
00304'000000 FORCE: 0
00305'000000 NPREM: 0
00306'000000 L:     0
00307'000000 XA:    0
00310'000000 YA:    0
00311'000000 YB:    0
00312'000000 FY:    0
                    .END
```

```
                        .TITL   MOTIO
                ;ROUTINE TO APPLY LAW OF MOTION TO ALL BLOCKS
                        .ENT    .MOT,.ROT,.TREC
                        .EXTD   .M1,.DISB,.REBX,.PFLG
                        .ZREL
00000-000001' .MOT:     MOT
00001-000140  .ROT:     140
00002-000040  .TREC:    40      ;1/TDEL
                        .NREL
00000'000000  SAVE:     0
00001'054777  MOT:      STA     3,SAVE
00002'034001$           LDA     3,.M1
00003'054547  MOT1:     STA     3,BLOCK
00004'031400            LDA     2,0,3
00005'151005            MOV     2,2,SNR
00006'002772            JMP     @SAVE    ;EXIT!
00007'021014            LDA     0,14,2   ;AREA
00010'101005            MOV     0,0,SNR
00011'000524            JMP     SKIP     ;ZERO AREA. SKIP!
00012'021000            LDA     0,0,2
00013'024540            LDA     1,FMSK   ;TO DETECT "FIXED" FLAG
00014'107404            AND     0,1,SZR
00015'000520            JMP     SKIP
00016'021007            LDA     0,7,2    ;FXSUM
00017'025005            LDA     1,5,2    ;OLD X-VEL
00020'004535            JSR     ADDMX
00021'045005            STA     1,5,2    ;NEW X-VEL
00022'050532            STA     2,SV2
00023'030002-           LDA     2,.TREC
00024'102400            SUB     0,0
00025'135000            MOV     1,3      ;KEEP FOR SIGN
00026'125112            MOVL#   1,1,SZC
00027'124400            NEG     1,1
00030'146512            SUBL#   2,1,SZC ;BYPASS IF ANSWER WILL BE 0
00031'000516            JMP     FLIP
00032'073101            DIV              ;INTEGER DIVIDE
00033'030521            LDA     2,SV2
00034'021002            LDA     0,2,2    ;XC(LOW)
00035'175112            MOVL#   3,3,SZC
00036'000405            JMP     FLIT     ;WAS NEGATIVE
00037'123023            ADDZ    1,0,SNC
00040'000417            JMP     OK
00041'011001            ISZ     1,2      ;INCREMENT XC(HIGH)
00042'000405            JMP     CHECK
00043'124400  FLIT:     NEG     1,1
00044'123022            ADDZ    1,0,SZC
00045'000412            JMP     OK
00046'015001            DSZ     1,2      ;DECREMENT XC(HIGH)
00047'045020  CHECK:    STA     1,20,2
00050'041002            STA     0,2,2
00051'024501            LDA     1,BLOCK
00052'006003$           JSR     @.REBX   ;RE-CLASSIFY THIS BLOCK
00053'034004$           LDA     3,.PFLG
00054'175005            MOV     3,3,SNR
00055'006002$           JSR     @.DISB
00056'000403            JMP     NUT
00057'045020  OK:       STA     1,20,2   ;DELTA-XC
00060'041002            STA     0,2,2    ;NEW XC(LOW)
              ;
00061'021016  NUT:      LDA     0,16,2   ;FYSUM
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00062'025015          LDA     1,15,2  ;OLD Y-VEL
00063'004472          JSR     ADDMX
00064'045015          STA     1,15,2  ;NEW Y-VEL
00065'030002-         LDA     2,.TREC
00066'102400          SUB     0,0     ;CLEAR HI PART
00067'135000          MOV     1,3     ;SAVE FOR SIGN
00070'125112          MOVL#   1,1,SZC
00071'124400          NEG     1,1
00072'146512          SUBL#   2,1,SZC ;BYPASS IF ANSWER WILL BE 0
00073'000451          JMP     FLOP
00074'073101          DIV     ;INTEGER DIVIDE
00075'030457          LDA     2,SV2
00076'021004          LDA     0,4,2   ;YC(LOW)
00077'175112          MOVL#   3,3,SZC
00100'000405          JMP     FLITS
00101'123023          ADDZ    1,0,SNC
00102'000417          JMP     OKS
00103'011003          ISZ     3,2     ;INCREMENT YC(HIGH)
00104'000405          JMP     CHECS
00105'124400  FLITS:  NEG     1,1
00106'123022          ADDZ    1,0,SZC
00107'000412          JMP     OKS
00110'015003          DSZ     3,2     ;DECREMENT YC(HIGH)
00111'045021  CHECS:  STA     1,21,2
00112'041004          STA     0,4,2
00113'024437          LDA     1,BLOCK
00114'006003S         JSR     @.REBX  ;RE-CLASSIFY
00115'034004$         LDA     3,.PFLG
00116'175005          MOV     3,3,SNR
00117'006002S         JSR     @.DISB  ;PLOT JUST THIS BLOCK
00120'000460          JMP     CLOT
00121'045021  OKS:    STA     1,21,2  ;DELTA-YC
00122'041004          STA     0,4,2   ;NEW YC(LOW)
              ;
00123'000455          JMP     CLOT    ;NOW FOR MOMENTS
              ;
00124'021023  CLOT1:  LDA     0,23,2  ;X LOAD
00125'041007          STA     0,7,2   ;INIT. XFSUM
00126'021024          LDA     0,24,2  ;Y LOAD
00127'025014          LDA     1,14,2  ;GRAVITY FORCE
00130'122400          SUB     1,0
00131'041016          STA     0,16,2  ;INIT. YFSUM
00132'102400          SUB     0,0
00133'041017          STA     0,17,2  ;SET MSUM TO 0
00134'000405          JMP     PAST
00135'102400  SKIP:   SUB     0,0
00136'041007          STA     0,7,2   ;XFSUM=0
00137'041016          STA     0,16,2  ;YFSUM=0
00140'041017          STA     0,17,2  ;MSUM=0
00141'034411  PAST:   LDA     3,BLOCK
00142'175400          INC     3,3
00143'000640          JMP     MOT1
00144'030410  FLOP:   LDA     2,SV2
00145'041021          STA     0,21,2  ;SET DELTA-YC TO 0
00146'000432          JMP     CLOT
00147'030405  FLIP:   LDA     2,SV2
00150'041020          STA     0,20,2
00151'000710          JMP     NUT
00152'000000  BLOCK:  0
00153'014000  FMSK:   14000   ;"FIXED" MASK
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00154'000000  SV2:    0
              ;
              ;TO ADD AC0 TO AC1, WITH AN UPPER
              ;LIMIT SET TO THE ANSWER IN AC1
00155'125020  ADDMX:  MOVZ    1,1       ;CLEAR CARRY
00156'125112          MOVL#   1,1,SZC
00157'000405          JMP     A1
00160'101113          MOVL#   0,0,SNC
00161'000407          JMP     POS       ;BOTH +VE
00162'107000  DIF:    ADD     0,1       ;BOTH SIGNS DIFFERENT
00163'001400          JMP     0,3       ;EXIT
00164'101113  A1:     MOVL#   0,0,SNC
00165'000775          JMP     DIF       ;BOTH DIF
00166'124400          NEG     1,1       ;BOTH -VE
00167'100440          NEGO    0,0       ;NEGATE BOTH. SET CARRY
00170'107000  POS:    ADD     0,1
00171'020406          LDA     0,MAX
00172'106432          SUBZ#   0,1,SZC ;LIMIT MAX VELOCITY
00173'105000          MOV     0,1
00174'125002          MOV     1,1,SZC ;FLAG?
00175'124400          NEG     1,1       ;YES, NEGATE!
00176'001400          JMP     0,3       ;EXIT
00177'037777  MAX:    37777
00200'126400  CLOT:   SUB     1,1       ;CLEAR LOWER
00201'021017          LDA     0,17,2    ;MSUM
00202'031013          LDA     2,13,2    ;I
00203'115000          MOV     0,3       ;SAVE M FOR LATER
00204'101112          MOVL#   0,0,SZC
00205'100400          NEG     0,0       ;ABS(MSUM)
00206'142432          SUBZ#   2,0,SZC ;CHECK FOR OVERFLOW
00207'124001          COM     1,1,SKP
00210'073101          DIV
00211'125220          MOVZR   1,1       ;) .ROT ERR
00212'125220          MOVZR   1,1       ;)/8
00213'125220          MOVZR   1,1       ;)
00214'175102          MOVL    3,3,SZC
00215'124400          NEG     1,1       ;RESTORE SIGN
00216'121000          MOV     1,0
00217'030735          LDA     2,SV2
00220'025006          LDA     1,6,2     ;OLD ALPHA-DOT
00221'004734          JSR     ADDMX
00222'045006          STA     1,6,2     ;NEW ALPHA-DOT
00223'030001-         LDA     2,.ROT
00224'102400          SUB     0,0
00225'135000          MOV     1,3
00226'125112          MOVL#   1,1,SZC
00227'124400          NEG     1,1
00230'146513          SUBL#   2,1,SNC ;CHECK FOR UNDERFLOW
00231'000410          JMP     TREE
00232'030722          LDA     2,SV2
00233'041022          STA     0,22,2    ;ZERO DELTA-ALPHA
00234'000670          JMP     CLOT1     ;NO MORE TO DO
00235'024715  CLOT2:  LDA     1,BLOCK
00236'006003S         JSR     @.REBX
00237'000665          JMP     CLOT1
00240'040000  TEST:   40000
00241'073101  TREE:   DIV
00242'030712          LDA     2,SV2
00243'175102          MOVL    3,3,SZC
00244'124400          NEG     1,1
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00245'021012          LDA    0,12,2  ;ALPHA(OLD)
00246'123000          ADD    1,0     ;ADD IN D-ALPHA
00247'125120          MOVZL  1,1     ;MAKE UP TOTAL SHIFT
00250'125120          MOVZL  1,1     ;  TO 8 BITS
00251'125120          MOVZL  1,1
00252'045022          STA    1,22,2  ;DELTA-ALPHA
00253'040514          STA    0,SIGN  ;KEEP SIGN FOR LATER
00254'105102          MOVL   0,1,SZC ;-VE? (GARBAGE IN AC1)
00255'100400          NEG    0,0     ;YES (C IS SET)
00256'024762          LDA    1,TEST
00257'122513          SUBL#  1,0,SNC ;IS ALPH>= 1/64?
00260'000405          JMP    CHAN    ;YES. INCR. COS & SIN
00261'101002          MOV    0,0,SZC ;WAS SIGN -VE?
00262'100400          NEG    0,0     ;YES. RESTORE IT
00263'041012          STA    0,12,2  ;ALPHA(NEW)
00264'000640          JMP    CLOT1   ;FINISHED!
00265'122462  CHAN:   SUBC   1,0,SZC ;SUBTRACT ALPH(MAX)
00266'100400          NEG    0,0
00267'041012          STA    0,12,2  ;ALPHA(NEW)
00270'024500          LDA    1,AMAX
00271'031011          LDA    2,11,2  ;SIN
00272'102400          SUB    0,0
00273'073301          MUL            ;MULT. BY AMAX (1/64)
00274'125112          MOVL#  1,1,SZC
00275'101400          INC    0,0     ;ROUND UP
00276'030656          LDA    2,SV2   ;(SIN*AMAX NOW IN CA0)
00277'025000          LDA    1,0,2   ;SIN FLAG
00300'044471          STA    1,SFLAG
00301'125100          MOVL   1,1     ;PUT FLAG IN CARRY
00302'034465          LDA    3,SIGN  ;D(ALPHA) FLAG
00303'175112          MOVL#  3,3,SZC
00304'175060          MOVC   3,3
00305'125112          MOVL#  1,1,SZC ;IS COS FLAG SET?
00306'125060          MOVC   1,1     ;YES. COMP. CARRY
00307'035010          LDA    3,10,2  ;OLD COS
00310'125003          MOV    1,1,SNC ;SAME SIGNS, C & D(C)?
00311'000404          JMP    CARO    ;YES. SUBTRACT!
00312'117022          ADDZ   0,3,SZC ;COS+D(COS)
00313'176000          ADC    3,3     ;SET TO MAX IF OVERFLOW
00314'000413          JMP    PRUNE
00315'116422  CARO:   SUBZ   0,3,SZC ;COS-D(COS)
00316'000411          JMP    PRUNE
00317'174400          NEG    3,3
00320'025000          LDA    1,0,2
00321'125100          MOVL   1,1
00322'125100          MOVL   1,1
00323'125060          MOVC   1,1     ;COMPLEMENT COS FLAG
00324'125200          MOVR   1,1
00325'125200          MOVR   1,1
00326'045000          STA    1,0,2   ;UPDATE CONTROL WORD
00327'025010  PRUNE:  LDA    1,10,2  ;OLD COS
00330'055010          STA    3,10,2  ;NEW COS
00331'030437          LDA    2,AMAX
00332'102400          SUB    0,0
00333'073301          MUL
00334'125112          MOVL#  1,1,SZC
00335'101400          INC    0,0     ;ROUND UP
00336'024433          LDA    1,SFLAG ;SIN FLAG
00337'125100          MOVL   1,1     ;BECOMES COS FLAG
00340'125100          MOVL   1,1     ;NOW IN CARY
```

```
---
00341'034426          LDA     3,SIGN   ;D(ALPHA) FLAG
00342'175112          MOVL#   3,3,SZC
00343'175060          MOVC    3,3
00344'030610          LDA     2,SV2
00345'025000          LDA     1,0,2    ;NEW CONTROL WORD
00346'125112          MOVL#   1,1,SZC ;IS SIN FLAG SET?
00347'125060          MOVC    1,1      ;YES. COMPLEMENT C
00350'035011          LDA     3,11,2   ;OLD SIN
00351'125002          MOV     1,1,SZC ;SAME SIGNS, S & D(S) ?
00352'000404          JMP     SARO     ;NO. SUBTRACT!
00353'117022          ADDZ    0,3,SZC ;SIN+D(SIN)
00354'176000          ADC     3,3      ;OVERFLOW
00355'000410          JMP     PLUM
00356'116422  SARO:   SUBZ    0,3,SZC ;SIN - D(SIN)
00357'000406          JMP     PLUM     ;NO SIGN CHANGE
00360'174400          NEG     3,3
00361'125100          MOVL    1,1
00362'125060          MOVC    1,1      ;COMPLEMENT SIN FLAG
00363'125200          MOVR    1,1
00364'045000          STA     1,0,2    ;UPDATE CONTROL WORD
00365'055011  PLUM:   STA     3,11,2   ;NEW SIN
00366'000647          JMP     CLOT2    ;ROTATION DONE
00367'000000  SIGN:   0
00370'001000  AMAX:   1000     ;1/128 (DEC)
00371'000000  SFLAG:  0
                      .END
```

```
                        .TITL   DISPL
                   ;TO DISPLAY ALL BLOCKS, CENTROIDS ON
                   ; THE SCREEN, OR ON PAPER
                   ;
                   ;       JSR @.DISS  ...  SCREEN ENTRY
                   ;
                   ;       JSR @.DISP  ...  PAPER ENTRY
                   ;
                   ;       JSR @.DISB  ...  PLOT SINGLE BLOCK
                   ;                        ON THE SCREEN
                   ;                        (AC2: BLOCK POINTER)
                   ;
                   ;       JSR @.LPLS  ...  TO PLOT LOAD VECTORS
                   ;                        ON SCREEN
                   ;
                        .ENT    .DISS,.DISP,.DISB,.NVEC,.LPLS
                        .EXTD   .PLTS,.RLNC,.PON1,.PON2,.M1,.PRN1
                        .EXTD   .MSKR,.NUM,.SCAL,.LFAP,.LENG
                        .EXTD   .IPRN,.MESS,.ALPH,.UD,.AXIS
                        .EXTD   .PRES,.IPRN,.NVEC
                        .EXTN   FEET
                        .ZREL
00000-000000   .PLOT:   0
00001-000100'  .DISS:   DISS
00002-000056'  .DISP:   DISP
00003-000053'  .DISB:   DISB    ;SINGLE BLOCK ENTRY
00004-000271'  .LPLS:   LPLS
00005-000000   .NVEC:   0       ;FLAG TO PRINT LOADS
                        .NREL
00000'000001   DRIVE:   1
       000012           .RDX    10
               ;TO PLOT AXES....
00001'054444   AXES:    STA     3,AXSAV
00002'020444            LDA     0,A1
00003'024444            LDA     1,A2
00004'006001S           JSR     @.PLTS
00005'000000            0
00006'006016S           JSR     @.ALPH
00007'020017S           LDA     0,.UD
00010'101005            MOV     0,0,SNR
00011'002434            JMP     @AXSAV
00012'006014S           JSR     @.IPRN
00013'000004            4
00014'006015S           JSR     @.MESS
00015'177777            FEET
00016'000073            59
00017'001356            750
00020'020430            LDA     0,A3
00021'024430            LDA     1,A4
00022'006001S           JSR     @.PLTS
00023'000000            0
00024'006016S           JSR     @.ALPH
00025'020017S           LDA     0,.UD
00026'006014S           JSR     @.IPRN
00027'000004            4
00030'006015S           JSR     @.MESS
00031'000015'           FEET
00032'001415            781
00033'000043            35
00034'006020S           JSR     @.AXIS
```

```
---
00035'001412            778
00036'000001            1
00037'000001            1
00040'006020$           JSR     @.AXIS
00041'176366            -778
00042'000001            1
00043'000001            1
00044'002401            JMP     @AXSAV
00045'000000  AXSAV:    0
00046'000003  A1:       3
00047'001356  A2:       750
00050'001265  A3:       693
00051'000043  A4:       35
      000010            .RDX    8
              ;
              ;
00052'000273' DIR:      DIREC
00053'020001$ DISB:     LDA     0,.PLTS
00054'040000-           STA     0,.PLOT
00055'000465            JMP     SING
00056'054524  DISP:     STA     3,SV3
00057'020721  TRY:      LDA     0,DRIVE
00060'062074            DOB     0,LINC
00061'020460            LDA     0,BLK
00062'024455            LDA     1,NBLK
00063'030455            LDA     2,CORE
00064'050000-           STA     2,.PLOT
00065'006002$           JSR     @.RLNC  ;READ IN PAPER PLOT ROUTINE
00066'125005            MOV     1,1,SNR
00067'000403            JMP     .+3
00070'063077            HALT            ;TAPE ERROR
00071'000766            JMP     TRY
00072'020444            LDA     0,FFP
00073'040441            STA     0,FFR
00074'020012$           LDA     0,.LPAP ;LOADS NEEDED?
00075'101004            MOV     0,0,SZR
00076'006754            JSR     @DIR    ;YES
00077'000407            JMP     SUN
00100'020001$ DISS:     LDA     0,.PLTS
00101'040000-           STA     0,.PLOT ;SCREEN-PLOT POINTER
00102'020433            LDA     0,FFS
00103'040431            STA     0,FFR
00104'054476            STA     3,SV3
00105'004674            JSR     AXES    ;PLOT AXES ON SCREEN ONLY
00106'034005$ SUN:      LDA     3,.M1
00107'054472  RAIN:     STA     3,BPNT
00110'031400            LDA     2,0,3
00111'151005            MOV     2,2,SNR
00112'000414            JMP     FINAL   ;NO MORE BLOCKS
00113'021014            LDA     0,14,2  ;AREA
00114'101005            MOV     0,0,SNR ;ZERO?
00115'000406            JMP     WIND    ;YES, SKIP THIS BLOCK
00116'021000            LDA     0,0,2
00117'024505            LDA     1,FMSK
00120'123414            AND#    1,0,SZR ;FIXED BLOCK?
00121'006413            JSR     @FFR    ;YES, PRINT AN "F"
00122'004420            JSR     SING    ;PLOT THIS BLOCK
00123'034456  WIND:     LDA     3,BPNT
00124'175400            INC     3,3
00125'000762            JMP     RAIN
---
```

```
00126'102400  FINAL:  SUB     0,0
00127'126400          SUB     1,1
00130'006000-         JSR     @.PLOT  ;RESET BEAM/PEN TO LOWER
00131'000000          0               ; LEFT-HAND CORNER
00132'006016S         JSR     @.ALPH
00133'002447          JMP     @SV3    ;EXIT
00134'000000  FFR:    0
00135'000207' FFS:    FF
00136'000225' FFP:    LETT
00137'000001  NBLK:   1
00140'000440  CORE:   440
00141'000555  BLK:    555
              ;
00142'054435  SING:   STA     3,SB3   ;ROUTINE TO PLOT A BLOCK
00143'021001          LDA     0,1,2
00144'025003          LDA     1,3,2
00145'006000-         JSR     @.PLOT
00146'177777          -1
00147'021000          LDA     0,0,2
00150'024007S         LDA     1,.MSKR
00151'107400          AND     0,1     ;NUMBER OF POINTS
00152'044426          STA     1,NPNTS
00153'126400          SUB     1,1
00154'044427          STA     1,NP
00155'006003S         JSR     @.PON1  ;GET X,Y FOR FIRST POINT
00156'040426          STA     0,X0    ;REMEMBER THEM FOR
00157'044426          STA     1,Y0    ; LAST LINE.
00160'006000-         JSR     @.PLOT  ;PLOT A POINT
00161'000000          0               ;BEAM OFF/PEN UP
00162'000404          JMP     HAIL
00163'006004S FOG:    JSR     @.PON2  ;2ND, QUICK ENTRY
00164'006000-         JSR     @.PLOT
00165'000001          1               ;BEAM ON / PEN DOWN
00166'010415  HAIL:   ISZ     NP
00167'024414          LDA     1,NP
00170'014410          DSZ     NPNTS
00171'000772          JMP     FOG     ;HAVEN'T REACHED LAST POINT YET
00172'020412          LDA     0,X0    ;GET FIRST POINT BACK
00173'024412          LDA     1,Y0
00174'006000-         JSR     @.PLOT  ;PLOT IT
00175'000001          1
00176'002401          JMP     @SB3    ;EXIT
              ;
00177'000000  SB3:    0
00200'000000  NPNTS:  0
00201'000000  BPNT:   0
00202'000000  SV3:    0
00203'000000  NP:     0
00204'000000  X0:     0
00205'000000  Y0:     0
00206'000000  CSV3:   0
              ;TO PRINT "F" ON FIXED BLOCKS
00207'054777  FF:     STA     3,CSV3
00210'021001          LDA     0,1,2
00211'025003          LDA     1,3,2
00212'034411          LDA     3,FIVE
00213'163000          ADD     3,0
00214'167000          ADD     3,1
00215'006000-         JSR     @.PLOT  ;GET BEAM POSITIONED
00216'000000          0
```

```
00217'006016$          JSR     @.ALPH   ;ALPHA
00220'006006$          JSR     @.PRN1   ;PRINT "F"
00221'000106           "F
00222'002764           JMP     @CSV3
00223'000005  FIVE:    5
00224'014000  FMSK:    14000
              ;TO PLOT A LETTER ON PAPER
00225'054432  LETT:    STA     3,SNOT
00226'050433           STA     2,SV2
00227'030433           LDA     2,POINT
00230'102400           SUB     0,0
00231'040417           STA     0,MODE
00232'021000  PLOOP:   LDA     0,0,2    ;(X:Y)
00233'105305           MOVS    0,1,SNR
00234'000421           JMP     END
00235'034007$          LDA     3,.MSKR
00236'167400           AND     3,1      ;Y
00237'163400           AND     3,0      ;X
00240'151400           INC     2,2
00241'050417           STA     2,IT2
00242'030417           LDA     2,SV2
00243'035001           LDA     3,1,2    ;XG
00244'163000           ADD     3,0      ;XP
00245'035003           LDA     3,3,2    ;YG
00246'167000           ADD     3,1      ;YP
00247'006000-          JSR     @.PLOT
00250'000000  MODE:    0
00251'102520           SUBZL   0,0
00252'040776           STA     0,MODE
00253'030405           LDA     2,IT2
00254'000756           JMP     PLOOP
00255'030404  END:     LDA     2,SV2
00256'002401           JMP     @SNOT
00257'000000  SNOT:    0
00260'000000  IT2:     0
00261'000000  SV2:     0
00262'000263' POINT:   .+1
00263'007012           7012     ;LETTER "F"
00264'007005           7005
00265'002405           2405
00266'005005           5005
00267'005010           5010
00270'000000           0
              ;  TO PLOT LOAD VECTORS
00271'020001$ LPLS:    LDA     0,.PLTS
00272'040000-          STA     0,.PLOT
00273'054572  DIREC:   STA     3,RVEC
00274'034005$          LDA     3,.M1
00275'020010$          LDA     0,.NUM
00276'040563           STA     0,KNT
00277'054563           STA     3,PNT
00300'031400  REPT:    LDA     2,0,3
00301'021014           LDA     0,14,2
00302'101005           MOV     0,0,SNR
00303'000463           JMP     TRIP     ;SKIP ERASED BLOCK
00304'021001           LDA     0,1,2    ;XC
00305'025003           LDA     1,3,2    ;YC
00306'006000-          JSR     @.PLOT
00307'000000           0
00310'025014           LDA     1,14,2   ;WEIGHT
```

```
00311'044562          STA     1,WW
00312'050551          STA     2,AC2
00313'006011$         JSR     @.SCAL
00314'030547          LDA     2,AC2
00315'021001          LDA     0,1,2     ;XC
00316'035003          LDA     3,3,2     ;YC
00317'136400          SUB     1,3
00320'165000          MOV     3,1
00321'006000-         JSR     @.PLOT
00322'000001          1
00323'006016$         JSR     @.ALPH
00324'020547          LDA     0,WW
00325'006014$         JSR     @.IPRN
00326'000004          4
00327'030534          LDA     2,AC2
00330'021001          LDA     0,1,2     ;CENTROID AGAIN
00331'025003          LDA     1,3,2
00332'006000-         JSR     @.PLOT
00333'000000          0
00334'025023          LDA     1,23,2    ;X LOAD
00335'044536          STA     1,WW
00336'006011$         JSR     @.SCAL    ;SCALE IT
00337'030524          LDA     2,AC2
00340'021001          LDA     0,1,2     ;XC
00341'107000          ADD     0,1
00342'044522          STA     1,XVEC
00343'025024          LDA     1,24,2    ;Y LOAD
00344'044530          STA     1,VV
00345'006011$         JSR     @.SCAL
00346'030515          LDA     2,AC2
00347'021003          LDA     0,3,2     ;YC
00350'107000          ADD     0,1
00351'020513          LDA     0,XVEC    ;VECTOR NOW IN AC0;AC1
00352'006000-         JSR     @.PLOT
00353'000001          1
               ;
00354'020005-         LDA     0,.NVEC ;.NVEC IS THE FLAG TO PLOT/N.. E
00355'101005          MOV     0,0,SNR ;THE MAG. OF APPLIED LOADS
00356'000410          JMP     TRIP    ;0 MEANS NO PLOT
               ;
00357'006016$         JSR     @.ALPH
00360'020513          LDA     0,WW
00361'006014$         JSR     @.IPRN
00362'000004          4
00363'020511          LDA     0,VV
00364'006014$         JSR     @.IPRN
00365'000004          4
00366'010474  TRIP:   ISZ     PNT
00367'034473          LDA     3,PNT
00370'014471          DSZ     KNT
00371'000707          JMP     REPT
               ;
               ;TO PRINT JOINT PRESSURES
               ;
00372'030021$         LDA     2,.PRES
00373'151112  PLUM:   MOVL#   2,2,SZC
00374'002471          JMP     @RVEC     ;EXIT
00375'025000          LDA     1,0,2     ;CONTROL WORD
00376'020007$         LDA     0,.MSKR
00377'050467          STA     2,PR2
```

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```
00400'123400          AND     1,0      ;NB
00401'106700          SUBS    0,1      ;NP
00402'044465          STA     1,NPREM
00403'034005$         LDA     3,.M1
00404'117000          ADD     0,3
00405'031400          LDA     2,0,3    ;BLOCK POINTER
00406'006013$         JSR     @.LENG
00407'040451          STA     0,LENG
00410'021014          LDA     0,14,2
00411'101005          MOV     0,0,SNR
00412'000442          JMP     FRED     ;SKIP ERASED BLOCK
00413'006003$         JSR     @.PON1
00414'040454          STA     0,XAA
00415'044454          STA     1,YAA
00416'024451          LDA     1,NPREM
00417'125400          INC     1,1
00420'021000          LDA     0,0,2    ;CONTROL WD
00421'034007$         LDA     3,.MSKR
00422'163400          AND     3,0      ;NC
00423'106415          SUB#    0,1,SNR  ;CHECK FOR LAST CORNER
00424'126400          SUB     1,1
00425'006004$         JSR     @.PON2
00426'034442          LDA     3,XAA
00427'163220          ADDZR   3,0      ;(XA+XB)/2
00430'034441          LDA     3,YAA
00431'167220          ADDZR   3,1      ;(YA+YB)/2
00432'034440          LDA     3,NN5
00433'162400          SUB     3,0
00434'166400          SUB     3,1
00435'006001$         JSR     @.PLTS
00436'000000          0
00437'006016$         JSR     @.ALPH
00440'006006$         JSR     @.PRN1
00441'000052          "*
00442'030424          LDA     2,PR2
00443'025001          LDA     1,1,2    ;FORCE
00444'102440          SUBO    0,0
00445'030412          LDA     2,N125
00446'073301          MUL
00447'030411          LDA     2,LENG
00450'073101          DIV
00451'121000          MOV     1,0
00452'006014$         JSR     @.IPRN
00453'000005          5
00454'030412   FRED:  LDA     2,PR2
00455'031002          LDA     2,2,2    ;LINK
0045 '000715          JMP     PLUM
      000012          .RDX    10
00457'000175   N125:  125
      000010          .RDX    8
00460'000000   LENG:  0
00461'000000   KNT:   0
00462'000000   PNT:   0
00463'000000   AC2:   0
00464'000000   XVEC:  0
00465'000000   RVEC:  0
00466'000000   PR2:   0
00467'000000   NPREM: 0
00470'000000   XAA:   0
00471'000000   YAA:   0
```

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---
00472'000005  NN5:    5
00473'000000  WW:     0
00474'000000  VV:     0
                      .END
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```
                                .TITL   CONTR
                        ;DYNAMIC ITERATION CONTROL ROUTINE
                                .ENT    CONTR,.PFLG,.C100,.VEC,.LPAP,.UREP
                                .EXTD   .OVL,.GETT,.DISS,.MOT,.CURS,.PRN1,.HITC
                                .EXTD   .PLTS,.PAGE,.ALLB,.FORD,.M1,.NUM,.CPNT
                                .EXTD   .DISP,.SCAL,.LPLS,.VFAC,MU,.RLNC,.UINP
                                .EXTD   .REBE,.EMPT,.PON1,.PON2,.MSKR,.M3,.M5
                                .EXTD   .INP,.HITS,.PRN2,.ALPH,.TYP,.LENG,.MESS
                                .EXTD   .PSEG,.DISB,.IPRN,.READ,.WRIT,.STEP,.TPN
                                .EXTD   .LODE,.DCM,.MOVE,.KSET,.KET,.TIME
                                .EXTN   OPTIN
                                .ZREL
00000-000000    .LPAP:  0       ;HARD COPY LOAD-PLOT FLAG
00001-000000    .VEC:   0       ;VECTOR PLOT FLAG (1=PLOT, 0=DON'T)
00002-000000    .PFLG:  0
00003-000100    .C100:  100
00004-000023    .UREP:  23      ;UPDATE FREQUENCY
                                .NREL
00000'000000    UCNT:   0
                        ;
                        ;----MAIN CALCULATION CYCLE----
                        ;
00001'020004-   GRUNT:  LDA     0,.UREP
00002'040776            STA     0,UCNT
00003'006004S   DYN:    JSR     @.MOT   ;LAW OF MOTION
00004'006057S           JSR     @.KET   ;K.E.ROUTINE
00005'006013S           JSR     @.FORD  ;FORCE/DISPLACEMENT LAW
00006'006051S           JSR     @.STEP  ; INCREMENT CYCLE COUNTER
00007'006054S           JSR     @.DCM   ;DISP MACHINE
00010'063710            SKPDZ   TTI
00011'004407            JSR     OUT     ;KEY HAS BEEN HIT
00012'014766            DSZ     UCNT
00013'000770            JMP     DYN
00014'006012S           JSR     @.ALLB  ;UPDATE CONTACT LIST
00015'000764            JMP     GRUNT
                        ;
                        ;-------------------------------
                        ;
00016'000257'   RT3:    RET3
00017'100257'   RTT3:   @RET3
00020'056776    OUT:    STA     3,@RT3
00021'006040S           JSR     @.ALPH
00022'060510            DIAS    0,TTI   ;GET KEY CHARACTER
00023'030426            LDA     2,POINT ;POINTER TO KEY LIST
00024'000403            JMP     SEEK
00025'151400    NEXT:   INC     2,2
00026'151400            INC     2,2
00027'025000    SEEK:   LDA     1,0,2
00030'125015            MOV#    1,1,SNR ;CHECK FOR LIST END
00031'002766            JMP     @RTT3   ;CHARACTER NOT FOUND
00032'034413            LDA     3,MSK   ;RIGHT 7 BITS
00033'163400            AND     3,0
00034'137400            AND     1,3     ;JUST CHARACTER ALONE
00035'162414            SUB#    3,0,SZR
00036'000767            JMP     NEXT    ;NOT THIS ONE
00037'166405            SUB     3,1,SNR ;FOUND IT! GET FLAG IN AC1
00040'003001            JMP     @1,2    ;GO TO APPROPRIATE ROUTINE
00041'034407            LDA     3,STATU ;STATUS FLAG
00042'166415            SUB#    3,1,SNR ;IS PERMISSION GRANTED?
00043'003001            JMP     @1,2    ;YES. GO TO ROUTINE
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---
00044'002753          JMP     @RTT3    ;BACK FROM WHENCE YOU CAME
00045'000177  MSK:    177
00046'100000  RFLAG:  100000
00047'040000  SFLAG:   40000
00050'000000  STATU:  0
00051'000052' POINT:  .+1
              ;
              ;LIST OF POSSIBLE KEYS THAT CAN BE HIT---
              ;
00052'000104          "D
00053'000166'         DSPLY   ;RE-DRAW BLOCKS
00054'040120          "P+40000
00055'000135'         PHASE   ;GO TO PHASE 1
00056'040107          "G+40000
00057'000132'         GO      ;START DYNAMICS
00060'100123          "S+100000
00061'000124'         STOP    ;STOP DYNAMICS
00062'000132          "Z
00063'000172'         ZERO    ;SET ALL VELOCITIES TO ZERO
00064'100116          "N+100000
00065'000156'         NOPLT   ;ERASE SCREEN & SUPPRESS PLOTTING
00066'100101          "A+100000
00067'000162'         ACTIV   ;ACTIVATE PLOTTING AGAIN
00070'040111          "I+40000
00071'000210'         INPUT   ;INPUT DATA
00072'000110          "H
00073'000252'         HARD    ;MAKE HARD COPY
00074'000126          "V
00075'000260'         VEC     ;VECTOR DISPLAY
00076'000114          "L
00077'000271'         LPLOT   ;TO PLOT LOADS ONLY
00100'000124          "T
00101'000275'         TYPEN   ;TO PRINT PROP. TYPE #'S
00102'040112          "J+40000
00103'000417'         PINP    ;TO INPUT JOINT PRESSURE
00104'040122          "R+40000
00105'000425'         RP3     ;TO READ A P-3 FILE
00106'040127          "W+40000
00107'000432'         WP3     ;TO WRITE A P-3 FILE
00110'040103          "C+40000
00111'000434'         CUR     ;PUT UP CURSOR AND WAIT
00112'040130          "X+40000
00113'000151'         RESET   ;TO RESET CYCLE COUNTERS,ETC
00114'040121          "Q+40000
00115'000150'         TIME    ;TO CHANGE DYN FACS
00116'040115          "M+40000
00117'000145'         MOVM    ;TO SET DISP CONTROL
00120'040102          "B+40000
00121'000146'         BOLT    ;TO SET UP FORCE BLOCKS
00122'000000          0       ;END OF LIST
              ;
00123'000401  CONTR:  JMP     STOP
              ;----------
00124'020723  STOP:   LDA     0,SFLAG
00125'040723          STA     0,STATU ;"STOP" STATUS
00126'063610          SKPDN   TTI      ;WAIT FOR TTY
00127'000777          JMP     .-1
00130'004670          JSR     OUT
00131'000773          JMP     STOP
              ;----------
```

```
---
00132'020714 GO:      LDA     0,RFLAG
00133'040715          STA     0,STATU ;"RUN" STATUS
00134'000645          JMP     GRUNT
             ;----------
00135'060477 PHASE:   READS   0        ;CANT LEAVE W/0-UP
00136'101122          MOVEL   0,0,SZC
00137'000765          JMP     STOP
00140'006011S         JSR     @.PAGE
00141'102520          SUBEL   0,0
00142'006001S         JSR     @.OVL    ;OVERLAY #1
00143'063077          HALT             ;TAPE ERROR
00144'000775          JMP     .-3
             ;----------
00145'002055S MOVM:   JMP     @.MOVE
             ;---------------
00146'063077 BOLT:    HALT
00147'000755          JMP     STOP
             ;----------
00150'006060S TIME:   JSR     @.TIME
             ;----------
00151'006056S RESET:  JSR     @.RSET
00152'006011S         JSR     @.PAGE
00153'006052S         JSR     @.TPRN
00154'006003S         JSR     @.DISS
00155'002502          JMP     @RET3
             ;----------
00156'006011S NOPLT:  JSR     @.PAGE
00157'102520          SUBEL   0,0
00160'040002-         STA     0,.PFLG ;SUPPRESS PLOTTING
00161'002476          JMP     @RET3
             ;----------
00162'102400 ACTIV:   SUB     0,0
00163'040002-         STA     0,.PFLG ;RE-ACTIVATE PLOTTING
00164'006052S         JSR     @.TPRN  ;WRITE NO. OF ITERATIONS
00165'002472          JMP     @RET3
             ;----------
00166'006011S DSPLY:  JSR     @.PAGE  ;ERASE SCREEN
00167'006052S         JSR     @.TPRN  ;WRITE NO. OF ITERATIONS
00170'006003S         JSR     @.DISS  ;RE-DRAW SYSTEM
00171'002466          JMP     @RET3
             ;----------
00172'030014S ZERO:   LDA     2,.M1
00173'024015S         LDA     1,.NUM
00174'124400          NEG     1,1
00175'102400          SUB     0,0
00176'035000 ITER:    LDA     3,0,2
00177'041405          STA     0,5,3   ;X-VEL
00200'041406          STA     0,6,3   ;ALPHA-DOT
00201'041415          STA     0,15,3  ;Y-VEL
00202'151400          INC     2,2
00203'125404          INC     1,1,SZR
00204'000772          JMP     ITER
00205'006006S         JSR     @.PRN1
00206'000007          7               ;RING BELL
00207'002450          JMP     @RET3
             ;----------
             ; INPUT ROUTINE-- FRICTION,LOADS,UNITS & OPTIONS
             ;
00210'006043S INPUT:  JSR     @.MESS
00211'001617'         INMS
```

```
---
00212'177324                 -300.
00213'001212                 650.
00214'006002$ DOVER:     JSR      @.GETT    ;WAIT FOR CHAR
00215'024426             LDA      1,CRGRT
00216'106415             SUB#     0,1,SNR
00217'002440             JMP      @RET3     ;CHANGED YOUR MIND
00220'024424             LDA      1,CHRF
00221'1 ...              SUB#     0,1,SZR
00222'000403             JMP      .+3
00223'006035$            JSR      @.INP     ; GO TO INPUT FRICTION
00224'002433             JMP      @RET3
00225'024420             LDA      1,CHRU
00226'106414             SUB#     0,1,SZR
00227'000403             JMP      .+3
00230'006025$            JSR      @.UINP    ;GO TO INPUT UNITS
00231'002426             JMP      @RET3
00232'024414             LDA      1,CHRL
00233'106414             SUB#     0,1,SZR
00234'000403             JMP      .+3
00235'006414             JSR      @LODO     ;GO TO INPUT LOADS
00236'002421             JMP      @RET3
00237'024410             LDA      1,CHRO
00240'106415             SUB#     0,1,SNR
00241'002407             JMP      @OPTNN    ;GO TO SET OPTIONS
00242'000752             JMP      DOVER     ; DO IT OVER
00243'000015  CRGRT:     15
00244'000106  CHRF:      "F
00245'000125  CHRU:      "U
00246'000114  CHRL:      "L
00247'000117  CHRO:      "O
00250'177777  OPTNN:     OPTIN
00251'001121' LODO:      ONLY
              ;----------
              ;HARD:     READS    0          ;CHECK FOR SW. 0
              ;          MOVEL    0,0,SZC    ;OFF=4631,ON=PLOTTER
              ;          JMP      PLTR
00252'006006$ HARD:      JSR      @.PRNI
00253'000033             27.                 ;ASCII ESC
00254'006006$            JSR      @.PRNI
00255'000027             23.                 ;ASCII ETB
00256'002401             JMP      @RET3
              ;PLTR:     JSR      @.DISP
              ;          JMP      @RET3
              ;----------
00257'000000  RET3:      0
              ;----------
00260'102520  VEC:       SUBZL    0,0
00261'040001-            STA      0,.VEC     ;SET VECTOR PLOT FLAG
00262'006004$            JSR      @.MOT
00263'006057$            JSR      @.KET
00264'006013$            JSR      @.FORD     ;ONE SCAN FOR PLOTTING
00265'006051$            JSR      @.STEP     ;INCREMENT CYCLE COUNTER
00266'102400             SUB      0,0
00267'040001-            STA      0,.VEC     ;KNOCK DOWN FLAG
00270'002767             JMP      @RET3      ;EXIT
              ;----------
00271'006021$ LPLOT:     JSR      @.[illegible]
00272'102520             SUBZL    [illegible]
00273'040000-            STA      [illegible]
00274'002763             JMP      [illegible]
```

AD-A084 693 MINNESOTA UNIV MINNEAPOLIS DEPT OF CIVIL AND MINING --ETC F/G 13/2
RATIONAL DESIGN OF TUNNEL SUPPORTS: AN INTERACTIVE GRAPHICS BAS--ETC(U)
SEP 79 M D VOEGELE DACW45-74-C-0066

UNCLASSIFIED WES/TR/GL-79-15 NL

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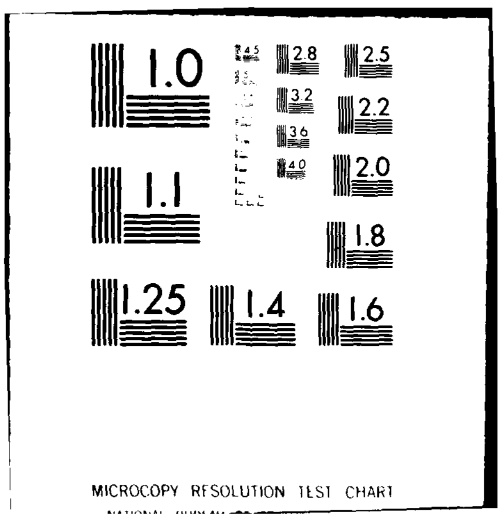
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MICROCOPY RESOLUTION TEST CHART

```
                  ;---------
                  ;TO PRINT TYPE #'S ON BLOCK EDGES
00275'034014S TYPEN:  LDA     3,.M1
00276'054502          STA     3,BLOCK
                  ;SCAN BLOCKS---
00277'031400  BEGIN:  LDA     2,0,3
00300'151005          MOV     2,2,SNR
00301'002756          JMP     @RET3
00302'021014          LDA     0,14,2
00303'101005          MOV     0,0,SNR
00304'000440          JMP     NEXT1
                  ;SCAN SIDES...
00305'021000          LDA     0,0,2
00306'024032S         LDA     1,.MSKR
00307'107400          AND     0,1
00310'044471          STA     1,NPNTS
00311'126400          SUB     1,1
00312'044470          STA     1,NPP
00313'006030S         JSR     @.PON1
00314'040467          STA     0,X0
00315'040470          STA     0,XA
00316'044466          STA     1,Y0
00317'044470          STA     1,YA
00320'024462          LDA     1,NPP
00321'000414          JMP     DOWN
00322'125400  BACK:   INC     1,1
00323'006031S         JSR     @.PON2
00324'040462          STA     0,XB
00325'044463          STA     1,YB
00326'004421          JSR     TPRNT
00327'010453          ISZ     NPP
00330'024452          LDA     1,NPP
00331'020455          LDA     0,XB
00332'040453          STA     0,XA
00333'020455          LDA     0,YB
00334'040453          STA     0,YA
00335'014444  DOWN:   DSZ     NPNTS
00336'000764          JMP     BACK
00337'020444          LDA     0,X0
00340'040446          STA     0,XB
00341'020443          LDA     0,Y0
00342'040446          STA     0,YB
00343'004404          JSR     TPRNT
                  ;END OF SIDE SCAN
00344'010434  NEXT1:  ISZ     BLOCK
00345'034433          LDA     3,BLOCK
00346'000731          JMP     BEGIN
                  ;END OF BLOCK SCAN
                  ;
00347'054430  TPRNT:  STA     3,TPSAV
00350'024432          LDA     1,NPP
00351'006041S         JSR     @.TYP     ;GET TYPE #, THIS EDGE
00352'101005          MOV     0,0,SNR ;DEFAULT
00353'002424          JMP     @TPSAV
00354'040435          STA     0,TYPE
00355'020430          LDA     0,XA
00356'034430          LDA     3,XB
00357'163220          ADDZR   3,0       ;(XA+XB)/2
00360'034432          LDA     3,MOVE1
00361'162400          SUB     3,0
```

```
---
00362'024425          LDA     1,YA
00363'034425          LDA     3,YB
00364'167220          ADDER   3,1     ;(YA+YB)/2
00365'034425          LDA     3,MOVEI
00366'166400          SUB     3,1
00367'006010S         JSR     @.PLTS
00370'000000          0
00371'006040S         JSR     @.ALPH
00372'020417          LDA     0,TYPE
00373'034420          LDA     3,NN0
00374'163000          ADD     3,0     ;ASCII CHAR
00375'006037S         JSR     @.FRN2
00376'002401          JMP     @TPSAV
00377'000000 TPSAV:   0
00400'000000 BLOCK:   0
00401'000000 NPNTS:   0
00402'000000 NPP:     0
00403'000000 X0:      0
00404'000000 Y0:      0
00405'000000 XA:      0
00406'000000 XB:      0
00407'000000 YA:      0
00410'000000 YB:      0
00411'000000 TYPE:    0
00412'000006 MOVEI:   6
00413'000060 NN0:     "0
00414'001100' FLG:    FLAG
             ;----------
00415'006025S UINP:   JSR     @.UINP
00416'002641          JMP     @RET3
             ;----------
00417'006043S PINP:   JSR     @.MESS
      000012          .RDX    10
00420'001461'         PMESS
00421'177324          -300
00422'001274          700
      000010          .RDX    8
00423'006044S         JSR     @.PSEG
00424'002633          JMP     @RET3
             ;----------
00425'006047S RP3:    JSR     @.READ
00426'006011S         JSR     @.PAGE
00427'006052S         JSR     @.TPRN
00430'006003S         JSR     @.DISS
00431'002626          JMP     @RET3
             ;----------
00432'006050S WP3:    JSR     @.WRIT
00433'002624          JMP     @RET3
             ;-----------
00434'102400 CUR:     SUB     0,0
00435'042757          STA     0,@FLG  ;RESET PROP. CHNG. INDIC.
00436'006005S CURS:   JSR     @.CURS
00437'000522'         CHAR
00440'000641'         X
00441'000642'         Y
00442'006040S         JSR     @.ALPH
00443'020457          LDA     0,CHAR
00444'024462          LDA     1,C1
00445'106415          SUB#    0,1,SNR ;"1" BEEN HIT?
00446'002456          JMP     @LOADR
```

```
---
00447'024464          LDA     1,0
00450'106415          SUB#    0,1,SNR ;HAS "O" BEEN HIT ?
00451'002454          JMP     @ONE
00452'024456          LDA     1,U
00453'106415          SUB#    0,1,SNR ;HAS "U" BEEN HIT?
00454'000575          JMP     UNFIX   ;YES
00455'024455          LDA     1,E
00456'106415          SUB#    0,1,SNR ;HAS "E" BEEN HIT?
00457'000455          JMP     ERASE   ;YES
00460'024451          LDA     1,F
00461'106414          SUB#    0,1,SER ;HAS "F" BEEN HIT?
00462'002441          JMP     @SURFR  ;TRY PROPERTY KEYS
00463'006007S         JSR     @.HITC
00464'000641'         X
00465'000642'         Y
00466'000750          JMP     CURS
00467'021000          LDA     0,0,2   ;CONTROL WORD
00470'024427          LDA     1,FBIT  ;"FIXED" FLAG (BIT 3)
00471'107414          AND#    0,1,SZR ;ALREADY FIXED?
00472'000744          JMP     CURS
00473'123000          ADD     1,0     ;ADD IN FLAG
00474'041000          STA     0,0,2   ;PUT WORD BACK
00475'102400          SUB     0,0     ;SUPPRESS VELOCITIES
00476'041005          STA     0,5,2   ;X-VEL
00477'041006          STA     0,6,2   ;ALPHA-DOT
00500'041015          STA     0,15,2  ;Y-VEL
00501'041020          STA     0,20,2  ;DELTA-X
00502'041021          STA     0,21,2  ;DELTA-Y
00503'041022          STA     0,22,2  ;DELTA-ALPHA
00504'034415          LDA     3,FIVE
00505'021001          LDA     0,1,2   ;XC
00506'163000          ADD     3,0     ;XC+5
00507'025003          LDA     1,3,2   ;YC
00510'167000          ADD     3,1     ;YC+5
00511'006010S         JSR     @.PLTS
00512'000000          0               ;PUT BEAM TO RIGHT PLACE
00513'006040S         JSR     @.ALPH
00514'006006S         JSR     @.PRN1
00515'000106          "F
00516'000720          JMP     CURS
00517'010000  FBIT:   10000   ;MANUAL FIX BIT
00520'004000  MBIT:   4000    ;MASTER FIX BIT
00521'000005  FIVE:   5
00522'000000  CHAR:   0
00523'001020' SURFR:  SURF
00524'000672' LOADR:  LOAD
00525'001121' ONE:    ONLY
00526'000261  C1:     "1+200
00527'000262  C2:     "2+200
00530'000325  U:      "U+200
00531'000306  F:      "F+200
00532'000305  E:      "E+200
00533'000317  O:      "O+200
00534'006007S ERASE:  JSR     @.HITC
00535'000641'         X
00536'000642'         Y
00537'000677          JMP     CURS    ;NO HIT
00540'044503          STA     1,NB    ;BLOCK #
00541'006011S         JSR     @.PAGE
00542'006026S         JSR     @.REBE  ;PUT IN CORRECT BOXES
```

```
---
00543'102400          SUB    0,0
00544'041014          STA    0,14,2   ;SET AREA TO ZERO
00545'021000          LDA    0,0,2
00546'024032S         LDA    1,.MSKR
00547'123400          AND    1,0
00550'040477          STA    0,PCNT
00551'126400          SUB    1,1
00552'044472          STA    1,NP
                ;NEXT PART REMOVES ALL POINT ENTRIES
                ;BOX ARRAY
00553'006030S         JSR    @.PON1
00554'000403          JMP    PLACE
00555'024467  COW:    LDA    1,NP
00556'006031S         JSR    @.PON2
00557'034033S PLACE:  LDA    3,.M3
00560'030003-         LDA    2,.C100
00561'040465          STA    0,NX
00562'102400          SUB    0,0
00563'073101          DIV
00564'127120          ADDZL  1,1
00565'1271            ADDZL  1,1
00566'137000          ADD    1,3
00567'024457          LDA    1,NX
00570'102400          SUB    0,0
00571'073101          DIV
00572'137000          ADD    1,3
00573'054452          STA    3,OLD
00574'020447          LDA    0,NB
00575'024447          LDA    1,NP
00576'125300          MOVS   1,1
00577'123000          ADD    1,0      ;(NP:NB)
00600'035400          LDA    3,0,3    ;(NO CHECK FOR END)
00601'025400  ROUND:  LDA    1,0,3
00602'106415          SUB#   0,1,SNR
00603'000405          JMP    OOT      ;FOUND IT
00604'165400          INC    3,1
00605'044440          STA    1,OLD
00606'035401          LDA    3,1,3    ;LINK
00607'000772          JMP    ROUND
00610'025401  OOT:    LDA    1,1,3    ;THIS LINK
00611'046434          STA    1,@OLD
00612'010432          ISZ    NP
00613'014434          DSZ    PCNT
00614'000741          JMP    COW
                ;TO RETURN DEAD CONTACT ENTRIES TO EMPTY LIST
00615'034034S         LDA    3,.M5
00616'020425          LDA    0,NB
00617'117000          ADD    0,3
00620'054425          STA    3,OLD
00621'035400          LDA    3,0,3
00622'165000          MOV    3,1      ;KEEP FIRST ENTRY
00623'175112          MOVL#  3,3,SZC
00624'000411          JMP    EXIT     ;NO CONTCTS
00625'171000  NIT:    MOV    3,2      ;SAVE PREV. ADDR.(LAST?)
00626'035402          LDA    3,2,3    ;NEXT ENTRY
00627'175113          MOVL#  3,3,SNC
00630'000775          JMP    NIT      ;KEEP GOING DOWN CHAIN
00631'056414          STA    3,@OLD   ;PLUG INITIAL POINTER
00632'020027S         LDA    0,.EMPT
00633'041002          STA    0,2,2    ;STORE OLD EMPT POINTER
```

```
00634'044027S          STA     1,.EMPT
00635'006012S EXIT:    JSR     @.ALLB   ;UPDATE REMAINING CONTACTS
00636'006052S          JSR     @.TPRN
00637'006003S          JSR     @.DISS   ;RE-DRAW
00640'002410           JMP     @CURSR
00641'000000  X:       0
00642'000000  Y:       0
00643'000000  NB:      0
00644'000000  NP:      0
00645'000000  OLD:     0
00646'000000  NX:      0
00647'000000  PCNT:    0
00650'000436' CURSR:   CURS
00651'006007S UNFIX:   JSR     @.HITC
00652'000641'          X
00653'000642'          Y
00654'002774           JMP     @CURSR
00655'021000           LDA     0,0,2    ;TO RELEASE A BLOCK
00656'024642           LDA     1,MBIT   ;IS MASTER BIT SET?
00657'107414           AND#    0,1,SZR
00660'002770           JMP     @CURSR   ;YES, HARD LUCK!
00661'024636           LDA     1,FBIT
00662'107415           AND#    0,1,SNR  ;FIXED ALREADY?
00663'002765           JMP     @CURSR   ;NO CHANGE NECESSARY
00664'122400           SUB     1,0      ;REMOVE BIT
00665'041000           STA     0,0,2    ;PUT CONTROL WORD BACK
00666'006011S          JSR     @.PAGE
00667'006052S          JSR     @.TPRN
00670'006003S          JSR     @.DISS   ;RE-DRAW
00671'002757           JMP     @CURSR   ;CARRY ON
              ;-----------------------
              ;ROUTINE TO INPUT LOAD VECTORS FROM SCREEN
              ;
00672'006007S LOAD:    JSR     @.HITC
00673'000641'          X
00674'000642'          Y
00675'000521           JMP     SURF1    ;NO HIT; TRY SURFACE
00676'050501           STA     2,PNT1
00677'006006S          JSR     @.PRN1   ;RING BELL FOR HIT
00700'000007           7
00701'006005S          JSR     @.CURS
00702'000522'          CHAR
00703'001000'          XX
00704'001001'          YY
00705'006040S          JSR     @.ALPH
00706'020614           LDA     0,CHAR
00707'024620           LDA     1,C2
00710'106414           SUB#    0,1,SZR  ;IS IT "2" FOR 2ND POINT?
00711'002737           JMP     @CURSR   ;NO, SOMETHING ELSE
00712'006007S          JSR     @.HITC
00713'001000'          XX
00714'001001'          YY
00715'000422           JMP     BOG      ;HAVEN'T HIT A BLOCK
00716'034461           LDA     3,PNT1   ;FIRST POINT BACK
00717'156414           SUB#    2,3,SZR  ;COMPARE
00720'000417           JMP     BOG      ;ANOTHER BLOCK (COINCIDENCE)
00721'021023           LDA     0,23,2   ;HIT ON SAME BLOCK
00722'025024           LDA     1,24,2   ;YY LOAD
00723'123005           ADD     1,0,SNR
00724'002724           JMP     @CURSR   ;ZERO. RETURN!
```

```
00725'102400            SUB     0,0
00726'041023            STA     0,23,2  ;SET LOADS TO ZERO
00727'041024            STA     0,24,2
00730'006011S REDR:     JSR     @.PAGE
00731'006052S           JSR     @.TPRN
00732'006003S           JSR     @.DISS
00733'006021S           JSR     @.LPLS
00734'102520            SUBZL   0,0
00735'040000-           STA     0,.LPAP
00736'002712            JMP     @CURSR
00737'034440  BOG:      LDA     3,PNT1
00740'021401            LDA     0,1,3   ;XXC
00741'024437            LDA     1,XX    ;END 2
00742'106400            SUB     0,1     ;RELATIVE VECTOR
00743'030022S           LDA     2,.VFAC ;SCALING FACTOR
00744'102400            SUB     0,0
00745'073301            MUL
00746'021423            LDA     0,23,3  ;OLD XX LOAD
00747'040427            STA     0,OLDX
00750'045423            STA     1,23,3  ;NEW XX LOAD
00751'021403            LDA     0,3,3   ;YYC
00752'024427            LDA     1,YY
00753'106400            SUB     0,1
00754'102400            SUB     0,0
00755'073301            MUL
00756'021424            LDA     0,24,3  ;OLD YY LOAD
00757'045424            STA     1,24,3  ;NEW YY LOAD
00760'024416            LDA     1,OLDX
00761'107004            ADD     0,1,SZR ;SKIP IF BOTH ZERO
00762'000746            JMP     REDR    ;RE-DRAW ALL
00763'021401            LDA     0,1,3   ;XXC
00764'025403            LDA     1,3,3   ;YYC
00765'006010S           JSR     @.PLTS
00766'000000            0
00767'020411            LDA     0,XX
00770'024411            LDA     1,YY
00771'006010S           JSR     @.PLTS  ;PLOT SINGLE NEW VECTOR
00772'000001            1
00773'102520            SUBZL   0,0
00774'040000-           STA     0,.LPAP
00775'002653            JMP     @CURSR
00776'000000  OLDX:     0
00777'000000  PNT1:     0
01000'000000  XX:       0
01001'000000  YY:       0
              ; ROUTINE FOR INPUT OF SURFACE PROPERTY TYPES
01002'100257' RET3S:    @RET3
01003'000436' CURSS:    CURS
01004'000000  ZIMM:     0
01005'000000  DIGIT:    0
01006'000000  DIGAS:    0
01007'020000  LBIT:     20000
01010'000260  N0:       "0+200
01011'000271  N9:       "9+200
01012'000006  MOVE:     6
      000025  START=25
01013'000026  SS:       START+1
01014'000027  SL:       START+2
01015'007777  TMSK:     7777
01016'020772  SURF1:    LDA     0,N0
```

```
01017'101400            INC     0,0
01020'040766  SURF:     STA     0,DIGAS ;SAVE ASCII FORM OF DIGIT
01021'024767            LDA     1,N0
01022'030767            LDA     2,N9
01023'142033            ADCZ#   2,0,SNC ;CHECK FOR DIGIT 0 TO 9
01024'106032            ADCZ#   0,1,SEC
01025'000454            JMP     UTRY    ;NOT DIGIT. EXIT!
01026'122400            SUB     1,0     ;BINARY VALUE
01027'040756            STA     0,DIGIT
01030'006036S           JSR     @.HITS  ;FIND WHICH EDGES
01031'000641' XRR:      X
01032'000642' YRR:      Y
01033'002750            JMP     @CURSS  ;PUT UP CURSOR AGAIN
01034'054750            STA     3,EIMM
01035'010443            ISZ     FLAG    ;RECORD TYPE CHANGES
              ;STORE TYPE # IN APPROPRIATE WORD
01036'021000            LDA     0,0,2   ;CONTROL WORD
01037'034750            LDA     3,LBIT
01040'117414            AND#    0,3,SZR ;LONG BLOCK?
01041'000406            JMP     LONG
01042'135120            MOVZL   1,3
01043'157000            ADD     2,3
01044'020747            LDA     0,SS
01045'117000            ADD     0,3
01046'000406            JMP     NOSE
01047'135120  LONG:     MOVZL   1,3
01050'137000            ADD     1,3
01051'157000            ADD     2,3
01052'020742            LDA     0,SL
01053'117000            ADD     0,3
01054'021400  NOSE:     LDA     0,0,3
01055'024740            LDA     1,TMSK
01056'107400            AND     0,1     ;MASK OFF OLD TYPE #
01057'020726            LDA     0,DIGIT
01060'103120            ADDZL   0,0
01061'103120            ADDZL   0,0
01062'101300            MOVS    0,0     ;IN LEFT 4 BITS
01063'107000            ADD     0,1     ;ADD IN NEW TYPE #
01064'045400            STA     1,0,3   ;PUT COMPOSITE BACK
              ;PRINT DIGIT AT CENTRE OF EDGE
01065'030725            LDA     2,MOVE
01066'022743            LDA     0,@XRR
01067'142400            SUB     2,0
01070'026742            LDA     1,@YRR
01071'146400            SUB     2,1
01072'006010S           JSR     @.PLTS
01073'000000            0
01074'006040S           JSR     @.ALPH
01075'020711            LDA     0,DIGAS
01076'006037S           JSR     @.PRN2
01077'002705            JMP     @EIMM   ;RE-ENTER FOR FURTHER HITS
01100'000000  FLAG:     0
01101'020777  UTRY:     LDA     0,FLAG
01102'101005            MOV     0,0,SNR
01103'002677            JMP     @RET3S  ;EXIT,NO CHANGES
              ;TO REQUEST UPDATE CYCLE, STORING
              ;NEW TYPE #S IN CONTACT LISTS
01104'030016S           LDA     2,.CPNT
01105'[illegible]       LDA     0,0,2   ;NEW WORD
01106'043000            STA     0,@0,2
```

```
01107'006012S          JSR     @.ALLB  ;DO AN UPDATE
01110'030016S          LDA     2,.CPNT
01111'021001           LDA     0,1,2   ;OLD WORD
01112'043000           STA     0,@0,2
01113'002667           JMP     @RET3S  ;EXIT
                 ;
                 ;     ROUTINE TO PLOT SINGLE BLOCK
                 ;
0111[illegible]' FRIC:  FRAC
01115'[illegible]' RET3T:  @RET3S
01116'001457' AC2TS:   AC2SV
01117'001436' VET:     VETO
01120'001443' PD:      POS
                 ;
01121'006043S ONLY:    JSR     @.MESS
01122'001474'          OMESS
01123'177242           -350.
01124'001274           700.
01125'006005S OCUR:    JSR     @.CURS  ;SELECT SINGLE BLOCK
01126'001452'          OCHAR
01127'001453'          OX
01130'001454'          OY
01131'006007S          JSR     @.HITC  ;IS IT A BLOCK
01132'001453'          OX
01133'001454'          OY
01134'000771           JMP     OCUR    ;NO HIT RETURN
01135'052761           STA     2,@AC2TS        ;GOOD HIT RETURN
01136'006011S          JSR     @.PAGE
01137'006052S          JSR     @.TPRN
01140'032756           LDA     2,@AC2TS
01141'006045S          JSR     @.DISB  ;DISPLAY IT
01142'006043S          JSR     @.MESS
01143'001506'          CTMES
01144'177634           -100.
01145'001274           700.
01146'006043S          JSR     @.MESS
01147'001521'          XCMES
01150'000175           125.
01151'001236           670.
01152'032744           LDA     2,@AC2TS
01153'021001           LDA     0,1,2   ;X CENT
01154'006040S          JSR     @.ALPH
01155'006046S          JSR     @.IPRN  ;PRINT IT
01156'000005           5
01157'032737           LDA     2,@AC2TS
01160'021002           LDA     0,2,2   ;XC LO PRECIS
01161'006733           JSR     @FRIC
01162'006043S          JSR     @.MESS
01163'001527'          YCMES
01164'000175           125.
01165'001212           650.
01166'032730           LDA     2,@AC2TS
01167'021003           LDA     0,3,2   ;YCENT
01170'006040S          JSR     @.ALPH
01171'006046S          JSR     @.IPRN  ;PRINT IT
01172'000005           5
01173'032723           LDA     2,@AC2TS
01174'021004           LDA     0,4,2   ;YC LO PREC
01175'006717           JSR     @FRIC
01176'032720           LDA     2,@AC2TS        ;BLOCK POINTER
```

```
---
01177'021001          LDA     0,1,2    ;XC
01200'025003          LDA     1,3,2    ;YC
01201'006010S         JSR     @.PLTS
01202'000000          0
01203'021014          LDA     0,14,2   ;WEIGHT
01204'006040S         JSR     @.ALPH
01205'006046S         JSR     @.IPRN   ;PRINT IT
01206'000004          4
01207'006043S         JSR     @.MESS
01210'001547'         LDMES
01211'176504          -700.
01212'001274          700.
01213'006043S         JSR     @.MESS
01214'001556'         XLMES
01215'001325          725.
01216'001236          670.
01217'032677          LDA     2,@AC2TS          ;GET BLOCK POINTER
01220'021023          LDA     0,23,2   ;X LOAD
01221'101132          MOVZL#  0,0,SEC ;GET SIGN OF LOAD
01222'006675          JSR     @VET     ;PRINT "-"
01223'006675          JSR     @PO      ;PRINT "+"
01224'006040S         JSR     @.ALPH
01225'006046S         JSR     @.IPRN   ;PRINT IT
01226'000005          5
01227'006043S         JSR     @.MESS
01230'001612'         YLMES
01231'001325          725.
01232'001212          650.
01233'032663          LDA     2,@AC2TS
01234'021024          LDA     0,24,2   ; Y LOAD
01235'101132          MOVZL#  0,0,SEC ;GET SIGN OF LOAD
01236'006661          JSR     @VET
01237'006661          JSR     @PO      ;PRINT +
01240'006040S         JSR     @.ALPH
01241'006046S         JSR     @.IPRN   ;PRINT IT
01242'000005          5
01243'060477          READS   0        ;1 VEL,FSUMS,ETC
01244'101123          MOVZL   0,0,SNC
01245'000552          JMP     OMIT
01246'006043S         JSR     @.MESS
01247'001632'         XFSM
01250'001325          725.
01251'000702          450.
01252'032644          LDA     2,@AC2TS          ;GET BLOCK POINTER
01253'021007          LDA     0,7,2    ;XFORCE SUM
01254'101132          MOVZL#  0,0,SEC ;GET SIGN
01255'004561          JSR     VETO
01256'004565          JSR     POS
01257'006040S         JSR     @.ALPH
01260'006046S         JSR     @.IPRN
01261'000006          6
01262'006043S         JSR     @.MESS
01263'001641'         YFSM
01264'001325          725.
01265'000644          420.
01266'032630          LDA.    2,@AC2TS
01267'021016          LDA     0,16,2   ;Y FORCE SUM
01270'101132          MOVZL#  0,0,SEC ;GET SIGN
01271'[illegible]     JSR     VETO
01272'004551          JSR     POS
```

```
---
01273'006040S          JSR      @.ALPH
01274'006046S          JSR      @.IPRN
01275'000006           6
01276'006043S          JSR      @.MESS
01277'001650'          MSUM
01300'001325           725.
01301'000606           390.
01302'030555           LDA      2,AC2SV
01303'021017           LDA      0,17,2  ;MOMENT SUM
01304'101132           MOVZL#   0,0,SEC ;GET SIGN
01305'004531           JSR      VETO
01306'004535           JSR      POS
01307'006040S          JSR      @.ALPH
01310'006046S          JSR      @.IPRN
01311'000007           7
01312'006043S          JSR      @.MESS
01313'001655'          XVLM
01314'001325           725.
01315'000512           330.
01316'030541           LDA      2,AC2SV
01317'021005           LDA      0,5,2   ;X VELOCITY
01320'101132           MOVZL#   0,0,SEC
01321'004515           JSR      VETO
01322'004521           JSR      POS
01323'006040S          JSR      @.ALPH
01324'006046S          JSR      @.IPRN
01325'000006           6
01326'006043S          JSR      @.MESS
01327'001663'          YVLM
01330'001325           725.
01331'000454           300.
01332'030525           LDA      2,AC2SV
01333'021015           LDA      0,15,2  ;Y VELOCITY
01334'101132           MOVZL#   0,0,SEC
01335'004501           JSR      VETO
01336'004505           JSR      POS
01337'006040S          JSR      @.ALPH
01340'006046S          JSR      @.IPRN
01341'000006           6
01342'006043S          JSR      @.MESS
01343'001671'          RVLM
01344'001325           725.
01345'000416           270.
01346'030511           LDA      2,AC2SV
01347'021006           LDA      0,6,2   ;ROT VEL
01350'101132           MOVZL#   0,0,SEC
01351'004465           JSR      VETO
01352'004471           JSR      POS
01353'006040S          JSR      @.ALPH
01354'006046S          JSR      @.IPRN
01355'000006           6
01356'006043S          JSR      @.MESS
01357'001535'          SINE
01360'001325           725.
01361'000310           200.
01362'030475           LDA      2,AC2SV ;GET BLOCK POINTER
01363'021000           LDA      0,0,2   ;SIGN OF THE SINE
01364'101132           MOVZL#   0,0,SEC ;+=0,-=1
01365'004451           JSR      VETO
01366'004455           JSR      POS
---
```

```
01367'021011            LDA     0,11,2  ;GET THE SINE
01370'006046S           JSR     @.IPRN
01371'177772            -6
01372'006043S           JSR     @.MESS
01373'001542'           DALF
01374'001325            725.
01375'000252            170.
01376'030461            LDA     2,AC2SV
01377'021022            LDA     0,22,2  ;GET DEL THETA
01400'040416            STA     0,DELF  ;SAVE IT
01401'101133            MOVZL#  0,0,SNC ;- OR +
01402'000407            JMP     LUS     ;WAS POS
01403'004433            JSR     VETO    ;PRINT-
01404'000401            JMP     .+1     ;NO OP
01405'020411            LDA     0,DELF
01406'006046S           JSR     @.IPRN  ;PRINT IT
01407'177772            -6
01410'000407            JMP     .+7
01411'004432  LUS:      JSR     POS     ;PRINT +
01412'020404            LDA     0,DELF
01413'006046S           JSR     @.IPRN
01414'177772            -6
01415'000402            JMP     .+2
01416'000000  DELF:     0
01417'006043S OMIT:     JSR     @.MESS
01420'001563'           QUES
01421'000144            100.
01422'000144            100.
01423'060110  DOVR:     NIOS    TTI
01424'006002S           JSR     @.GETT
01425'006037S           JSR     @.PRN2
01426'024427            LDA     1,YCHAR
01427'106405            SUB     0,1,SNR
01430'000420            JMP     LODE
01431'024425            LDA     1,NCHAR
01432'106404            SUB     0,1,SZR
01433'000770            JMP     DOVR
01434'002401            JMP     @RT3T   ;EXIT
01435'101115' RT3T:     @RET3T
01436'054422  VETO:     STA     3,AC3SV
01437'006006S           JSR     @.PRN1
01440'000055            "-
01441'034417            LDA     3,AC3SV
01442'001401            JMP     1,3
01443'054415  POS:      STA     3,AC3SV
01444'006006S           JSR     @.PRN1
01445'000053            "+
01446'034412            LDA     3,AC3SV
01447'001400            JMP     0,3
01450'030407  LODE:     LDA     2,AC2SV ; GET BLOCK POINTER
01451'006053S           JSR     @.LODE  ;GO TO INPUT ROUTINE
01452'000000  OCHAR:    0
01453'000000  OX:       0
01454'000000  OY:       0
01455'000131  YCHAR:    "Y
01456'000116  NCHAR:    "N
01457'000000  AC2SV:    0
01460'000000  AC3SV:    0
              ;
01461'047111  PMESS:    .TXT    *IN
```

```
---
01462'052520  PU
01463'020124  T
01464'047512  JO
01465'047111  IN
01466'020124  T
01467'051120  PR
01470'051505  ES
01471'052523  SU
01472'042522  RE
01473'000123  S*
01474'042523  OMESS:   .TXT     *SE
01475'042514  LE
01476'052103  CT
01477'0514[illegible]  [illegible]
01500'047111  IN
01501'046107  GL
01502'020105  E
01503'046102  BL
01504'041517  OC
01505'000113  K*
01506'042503  CTMES:   .TXT     *CE
01507'052116  NT
01510'047522  RO
01511'042111  ID
01512'041440   C
01513'047517  OO
01514'042122  RD
01515'047111  IN
01516'052101  AT
01517'051505  ES
01520'000000  *
01521'020130  XCMES:   .TXT     *X
01522'042503  CE
01523'052116  NT
01524'047522  RO
01525'042111  ID
01526'000000  *
01527'020131  YCMES:   .TXT     *Y
01530'042503  CE
01531'052116  NT
01532'047522  RO
01533'042111  ID
01534'000000  *
01535'044523  SINE:    .TXT     *SI
01536'020116  N
01537'044124  TH
01540'052105  ET
01541'000101  A*
01542'042504  DALF:    .TXT     *DE
01543'020114  L
01544'044124  TH
01545'052105  ET
01546'000101  A*
01547'050101  LDMES:   .TXT     *AP
01550'046120  PL
01551'042511  IE
01552'020104  D
01553'047514  LO
01554'042101  AD
01555'000123  S*
```

```
---
01556'020130  XLMES:   .TXT    *X
01557'047514  LO
01560'042101  AD
01561'020040
01562'000000  *
01563'047504  QUES:    .TXT    *DO
01564'054440   Y
01565'052517  OU
01566'053440   W
01567'051511  IS
01570'020110  H
01571'047524  TO
01572'041440   C
01573'040510  HA
01574'043516  NG
01575'020105  E
01576'044124  TH
01577'020105  E
01600'047514  LO
01601'042101  AD
01602'020123  S
01603'020050  (
01604'020131  Y
01605'051117  OR
01606'047040   N
01607'024440   )
01610'037440   ?
01611'000040   *
01612'020131  YLMES:   .TXT    *Y
01613'047514  LO
01614'042101  AD
01615'020040
01616'000000  *
01617'044440  INMS:    .TXT    * I
01620'050116  NP
01621'052125  UT
01622'043040   F
01623'052454  ,U
01624'046054  ,L
01625'047440   O
01626'020122  R
01627'020117  O
01630'020077  ?
01631'000000  *
01632'020130  XFSM:    .TXT    *X
01633'047506  FO
01634'041522  RC
01635'020105  E
01636'052523  SU
01637'020115  M
01640'000000  *
01641'020131  YFSM:    .TXT    *Y
01642'047506  FO
01643'041522  RC
01644'020105  E
01645'052523  SU
01646'020115  M
01647'000000  *
01650'047515  MSUM:    .TXT    *MO
01651'027115  M.
```

```
01652'051440   S
01653'046525  UM
01654'000040   *
01655'020130  XVLM:     .TXT     *X
01656'042526  VE
01657'047514  LO
01660'044503  CI
01661'054524  TY
01662'000040   *
01663'020131  YVLM:     .TXT     *Y
01664'042526  VE
01665'047514  LO
01666'044503  CI
01667'054524  TY
01670'000040   *
01671'047522  RVLM:     .TXT     *RO
01672'027124  T.
01673'053040   V
01674'046105  EL
01675'020056  .
01676'000000  *
              ;TO PRINT FRACTION (WITH N DECIMAL
              ;PLACES) FOLLOWING HI PREC COORD
      000004  N=4       ; NO. OF DIGITS
01677'054413  FRAC:     STA      3,FSAV
01700'040413            STA      0,FR
01701'006006S           JSR      @.PRN1
01702'000056            ".
01703'024410            LDA      1,FR
01704'030410            LDA      2,C1000
01705'102400            SUB      0,0
01706'073301            MUL
01707'006046S           JSR      @.IPRN
01710'177774            -N
01711'002401            JMP      @FSAV
01712'000000  FSAV:     0
01713'000000  FR:       0
01714'023420  C1000:    10000.   ;SET AT 10**N
                        .END
```

```
                        .TITL   CYCLE
                ;SEVERAL ADDITIONAL UTILITY PROGRAMS
                        .ENT    OPTIN,.STEP,.TPRN
                        .ENT    .KET,.RSET
                        .EXTD   .IPRN,.PRN1,.MESS
                        .EXTD   .NVEC,.VFAC,.DISS,.PAGE
                        .EXTD   .PRN2,.GETT,.DBIN,MU
                        .EXTD   .MI,.VEC,.PFLG,.NUM
                        .EXTD   .MOT,.FORD
                        .EXTN   CONTR
                        .ZREL   .
00000-000123' .RSET:    CHNGIT
00001-000314' .STEP:    STEP
00002-000333' .TPRN:    TPRN
00003-000000  .ITLO:    0
00004-000000  .ITHI:    0
00005-000000  .OPTN:    0
00006-000000  .COPY:    0
00007-000000  .STOP:    0
00010-000001  .COPCT:   1
00011-000000  .KEFL:    0       ;0=NO KE CALC
00012-000011' .KET:     KET
00013-000005  .C10:5
                        .NREL
              ;
              ;ROUTINE TO SET VELOCITIES TO ZERO
              ;AT A KINETIC ENERGY PEAK
              ;
00000'000000  KRET:     0
00001'000000  POINT:    0
00002'000000  COUNT:    0
00003'000000  KHI:      0
00004'000000  KLO:      0
00005'000000  KOHI:     0
00006'000000  KOLO:     0
00007'000000  FLAG:     0
00010'000000  HYS:      0
              ;
00011'020011- KET:      LDA     0,.KEFL
00012'101005            MOV     0,0,SNR
00013'001400            JMP     0,3
00014'054764            STA     3,KRET
00015'034014$           LDA     3,.MI
00016'054763            STA     3,POINT
00017'024764            LDA     1,KHI
00020'044765            STA     1,KOHI
00021'024763            LDA     1,KLO
00022'044764            STA     1,KOLO
00023'024017$           LDA     1,.NUM
00024'044756            STA     1,COUNT
00025'102400            SUB     0,0
00026'040755            STA     0,KHI
00027'040755            STA     0,KLO
              ; TO FIND KINETIC ENERGY
00030'036751  ITER:     LDA     3,@POINT
00031'102520            SUBZL   0,0
00032'040755            STA     0,FLAG
              ; X VELOCITY
00033'031405            LDA     2,5,3
00034'151112  BACK:     MOVL#   2,2,SZC
```

```
---
00035'150400          NEG     2,2
00036'145000          MOV     2,1
00037'102400          SUB     0,0
00040'073301          MUL
00041'030742          LDA     2,KHI
00042'034742          LDA     3,KLO
00043'167022          ADDZ    3,1,SZC ; DOUBLE PREC ADD
00044'151400          INC     2,2
00045'143000          ADD     2,0
00046'040735          STA     0,KHI
00047'044735          STA     1,KLO
00050'014737          DSZ     FLAG
00051'000404          JMP     NEXT
                ; Y VELOCITY
00052'036727          LDA     3,@POINT
00053'031415          LDA     2,15,3
00054'000760          JMP     BACK
00055'010724    NEXT: ISZ     POINT
00056'014724          DSZ     COUNT
00057'000751          JMP     ITER
                ; CHECK ON HYSTERESIS COUNT
00060'010730          ISZ     HYS
00061'024723          LDA     1,KLO
00062'020721          LDA     0,KHI
00063'030722          LDA     2,KOHI
00064'034722          LDA     3,KOLO
00065'166422          SUBZ    3,1,SZC ;DOUBLE PREC SUB
00066'142401          SUB     2,0,SKP
00067'142000          ADC     2,0
00070'101123          MOVZL   0,0,SNC
00071'000431          JMP     NOPK
00072'024013-         LDA     1,.C10
00073'020715          LDA     0,HYS
00074'106032          ADCZ#   0,1,SZC
00075'000425          JMP     NOPK
                ; ZERO VELOCITIES
00076'030014S         LDA     2,.M1
00077'024017S         LDA     1,.NUM
00100'124400          NEG     1,1
00101'102400          SUB     0,0
00102'035000    ITRE: LDA     3,0,2
00103'041405          STA     0,5,3
00104'041406          STA     0,6,3
00105'041415          STA     0,15,3
00106'151400          INC     2,2
00107'125404          INC     1,1,SZR
00110'000772          JMP     ITRE
00111'176400          SUB     3,3
00112'054676          STA     3,HYS
00113'034016S         LDA     3,.PFLG ;INHIBIT PRINTING IN NOPLT
00114'175004          MOV     3,3,SZR
00115'000405          JMP     NOPK
00116'006003S         JSR     @.MESS
00117'000641'         KMS
00120'001522          850.
00121'000062          50.
00122'002656    NOPK: JMP     @KRET
                ;
                ;------------RESET ROUTINE ----
                ;
---
```

```
---
00123'054407  CHNGIT: STA     3,SAV3
00124'176400          SUB     3,3
00125'054004-         STA     3,.ITHI
00126'054003-         STA     3,.ITLO
00127'176520          SUBZL   3,3
00130'054010-         STA     3,.COPCT
00131'002401          JMP     @SAV3
00132'000000  SAV3:   0
              ;
              ;------- OPTION INPUT ROUTINE ----
              ;
00133'006007S OPTIN:  JSR     @.PAGE
00134'006003S         JSR     @.MESS
00135'000455'         OPTMS
00136'177242          -350.
00137'001274          700.
00140'006003S         JSR     @.MESS
00141'000467'         CRMS
00142'000062          50.
00143'001236          670.
00144'006011S OUT:    JSR     @.GETT
00145'024546          LDA     1,CRGRT
00146'106415          SUB#    0,1,SNR ;MUST EXIT
00147'000535          JMP     HOME
00150'006003S         JSR     @.MESS
00151'000523'         N1
00152'000310          200.
00153'001212          650.
00154'006003S         JSR     @.MESS
00155'000555'         Q1
00156'000113          75.
00157'001130          600.
00160'006011S OV1:    JSR     @.GETT
00161'024531          LDA     1,YCHR
00162'106414          SUB#    0,1,SZR
00163'000405          JMP     .+5
00164'006010S         JSR     @.PRN2  ;PRINT Y
00165'126520          SUBZL   1,1
00166'044004S         STA     1,.NVEC ;SET FLAG TO PRINT
00167'000407          JMP     CNT1    ;NEXT
00170'024521          LDA     1,NCHR  ;CHK FOR NO
00171'106414          SUB#    0,1,SZR
00172'000766          JMP     OV1
00173'006010S         JSR     @.PRN2  ;PRINT IT
00174'126440          SUBO    1,1
00175'044004S         STA     1,.NVEC ;INHIBIT PRINTING
00176'006003S CNT1:   JSR     @.MESS
00177'000605'         Q2
00200'000113          75.
00201'001046          550.
00202'006012S         JSR     @.DBIN
00203'044005S         STA     1,.VFAC ;SET SCALE FACT
00204'006003S         JSR     @.MESS
00205'001051'         Q6
00206'000113          75.
00207'000764          500.
00210'006011S OVR6:   JSR     @.GETT
00211'024501          LDA     1,YCHR
00212'106414          SUB#    0,1,SZR
00213'000405          JMP     .+5

---
```

```
00214'006010S         JSR     @.PRN2  ;PRINT Y
00215'126520          SUBZL   1,1
00216'044011-         STA     1,.KEFL ;SET FLG TO K.E. ZERO
00217'000407          JMP     CTNU    ;NEXT
00220'024471          LDA     1,NCHR
00221'106414          SUB#    0,1,SZR
00222'000766          JMP     OVR6
00223'006010S         JSR     @.PRN2
00224'126440          SUBO    1,1
00225'044011-         STA     1,.KEFL ;INHIB K.E.ZERO
00226'006003S CTNU:   JSR     @.MESS
00227'000646'         Q3
00230'000113          75.
00231'000702          450.
00232'006011S OV2:    JSR     @.GETT
00233'024456          LDA     1,NCHR
00234'106414          SUB#    0,1,SZR
00235'000405          JMP     .+5
00236'006010S         JSR     @.PRN2  ;PRINT N
00237'126440          SUBO    1,1
00240'044005-         STA     1,.OPTN ;NO OPTIONS
00241'000433          JMP     LAST
00242'024450          LDA     1,YCHR
00243'106414          SUB#    0,1,SZR
00244'000766          JMP     OV2
00245'006010S         JSR     @.PRN2  ;PRINT Y
00246'126520          SUBZL   1,1
00247'044005-         STA     1,.OPTN ;SET OPTION FLAG
00250'006003S         JSR     @.MESS
00251'000756'         N2
00252'000144          100.
00253'000620          400.
00254'006003S         JSR     @.MESS
00255'001010'         N3
00256'000175          125.
00257'000567          375.
00260'006003S         JSR     @.MESS
00261'000676'         Q4
00262'000113          75.
00263'000505          325.
00264'006012S         JSR     @.DBIN
00265'044006-         STA     1,.COPY
00266'006003S         JSR     @.MESS
00267'000727'         Q5
00270'000113          75.
00271'000423          275.
00272'006012S         JSR     @.DBIN
00273'044007-         STA     1,.STOP
00274'006003S LAST:   JSR     @.MESS
00275'001033'         N4
00276'000310          200.
00277'000257          175.
00300'006011S OV3:    JSR     @.GETT
00301'024412          LDA     1,CRGRT
00302'106414          SUB#    0,1,SZR
00303'000775          JMP     OV3
00304'006007S HOME:   JSR     @.PAGE
00305'006002-         JSR     @.TPRN
00306'006006S         JSR     @.DISS
00307'002401          JMP     @BAKK
```

```
---
00310'177777  BAKK:   CONTR
00311'000116  NCHR:   "N
00312'000131  YCHR:   "Y
00313'000015  CRGRT:  15
              ;
              ;----------ROUTINE TO STEP CYCLE COUNTER ---
              ;
              ;              JSR  @.STEP
              ;
00314'054523  STEP:   STA     3,SAV3P
00315'020003-         LDA     0,.ITLO
00316'024514          LDA     1,ITMAX
00317'101400          INC     0,0
00320'106415          SUB#    0,1,SNR
00321'000404          JMP     NOTCH
00322'040003-         STA     0,.ITLO
00323'034514          LDA     3,SAV3P
00324'001400          JMP     0,3      ;EXIT
00325'102400  NOTCH:  SUB     0,0
00326'040003-         STA     0,.ITLO ;RESET LO WORD
00327'010004-         ISZ     .ITHI   ;INCREMENT HI WORD
00330'004434          JSR     OPTON   ;CHECK OPTIONS
00331'034506          LDA     3,SAV3P
00332'001400          JMP     0,3      ;EXIT
              ;
              ;----------ROUTINE TO PRINT CYCLES----------
              ;
              ;             JSR    @.TPRN
              ;
00333'054501  TPRN:   STA     3,TERMITE
00334'060477          READS   0
00335'101222          MOVZR   0,0,SZC
00336'000425          JMP     OOT
00337'006003$         JSR     @.MESS
00340'000454'         MAT
00341'000702          450.
00342'001402          770.
00343'020004-         LDA     0,.ITHI
00344'006001$         JSR     @.IPRN  ;HI PART
00345'000005          5
00346'020003-         LDA     0,.ITLO
00347'006001$         JSR     @.IPRN  ;LO PART
00350'177774          -4      ;WITH LEADING ZEROS
00351'006003$         JSR     @.MESS
00352'000440'         CYC
00353'001116          590.
00354'001402          770.
00355'024013$         LDA     1,MU
00356'030453          LDA     2,C1000
00357'102400          SUB     0,0
00360'073301          MUL
00361'006001$         JSR     @.IPRN  ;PRINT DEFAULT MU
00362'177775          -3
00363'002451  OOT:    JMP     @TERMITE
              ;
              ;---------------------------
              ;
              ;  OPTION CHECKER
              ;
              ;
---
```

```
00364'054452  OPTON:  STA     3,SAVE3
00365'020005-         LDA     0,.OPTN ;ACTIVATE OPTIONS ?
00366'101005          MOV     0,0,SNR
00367'001400          JMP     0,3
00370'020006-         LDA     0,.COPY
00371'101004          MOV     0,0,SER
00372'004413          JSR     COPI
00373'020007-         LDA     0,.STOP
00374'101004          MOV     0,0,SER
00375'000403          JMP     BON
00376'034440          LDA     3,SAVE3
00377'001400          JMP     0,3
00400'024004- BON:    LDA     1,.ITHI
00401'106405          SUB     0,1,SNR
00402'002431          JMP     @CONTIN
00403'034433          LDA     3,SAVE3
00404'001400          JMP     0,3
              ;
00405'054430  COPI:   STA     3,SAV3A
00406'020004-         LDA     0,.ITHI
00407'024010-         LDA     1,.COPCT
00410'106414          SUB#    0,1,SER
00411'001400          JMP     0,3
00412'006002$         JSR     @.PRNI
00413'000007          7               ;RING BELL
00414'004717          JSR     TPRN
00415'006006$         JSR     @.DISS
00416'006002$         JSR     @.PRNI
00417'000033          27.             ;ASCII ESC
00420'006002$         JSR     @.PRNI
00421'000027          23.             ;ASCII ETB
00422'006007$         JSR     @.PAGE
00423'024010-         LDA     1,.COPCT
00424'030006-         LDA     2,.COPY
00425'147000          ADD     2,1
00426'044010-         STA     1,.COPCT
00427'034406          LDA     3,SAV3A
00430'001400          JMP     0,3
              ;
00431'001750  C1000:  1000.
00432'023420  ITMAX:  10000.
00433'000310' CONTIN: CONTR
00434'000000  TERMITE:0
00435'000000  SAV3A:  0
00436'000000  SAVE3:  0
00437'000000  SAV3P:  0
00440'041440  CYC:    .TXT    * C
00441'041531  YC
00442'042514  LE
00443'020123  S
00444'020040
00445'042504  DE
00446'040506  FA
00447'046125  UL
00450'020124  T
00451'052515  MU
00452'030075  =0
00453'000056  .*
00454'000040  MAT:    .TXT    * *
00455'040440  OPTMS:  .TXT    * A
```

```
---
00456'040526  VA
00457'046111  IL
00460'041101  AB
00461'042514  LE
00462'047440   O
00463'052120  PT
00464'047511  IO
00465'051516  NS
00466'000040   *
00467'020050  CRMS:      .TXT     *(
00470'044510  HI
00471'020124  T
00472'027103  C.
00473'027122  R.
00474'052040   T
00475'020117  O
00476'047507  GO
00477'041040   B
00500'041501  AC
00501'020113  K
00502'047516  NO
00503'020127  W
00504'020055  -
00505'047101  AN
00506'020131  Y
00507'052117  OT
00510'042510  HE
00511'020122  R
00512'042513  KE
00513'020131  Y
00514'047524  TO
00515'041440   C
00516'047117  ON
00517'044524  TI
00520'052516  NU
00521'020105  E
00522'000051  )*
00523'040450  N1:        .TXT     *(A
00524'051516  NS
00525'042527  WE
00526'020122  R
00527'046101  AL
00530'020114  L
00531'052521  QU
00532'051505  ES
00533'044524  TI
00534'047117  ON
00535'026523  S-
00536'052123  ST
00537'047101  AN
00540'040504  DA
00541'042122  RD
00542'040440   A
00543'051516  NS
00544'042527  WE
00545'051522  RS
00546'047072  :N
00547'031454  ,3
00550'041450  (C
00551'024522  R)
```

```
---
00552'047054   ,N
00553'047054   ,N
00554'000051   )*
00555'047504   Q1:      .TXT     *DO
00556'054440    Y
00557'052517   OU
00560'053440    W
00561'051511   IS
00562'020110   H
00563'047524   TO
00564'050040    P
00565'044522   RI
00566'052116   NT
00567'040440    A
00570'050120   PP
00571'044514   LI
00572'042105   ED
00573'046040    L
00574'040517   OA
00575'020104   D
00576'040526   VA
00577'052514   LU
00600'051505   ES
00601'024040    (
00602'027531   Y/
00603'024516   N)
00604'000077   ?*
00605'044127   Q2:      .TXT     *WH
00606'052101   AT
00607'053440    W
00610'052517   OU
00611'042114   LD
00612'054440    Y
00613'052517   OU
00614'046040    L
00615'045511   IK
00616'020105   E
00617'051501   AS
00620'052040    T
00621'042510   HE
00622'053040    V
00623'041505   EC
00624'047524   TO
00625'020122   R
00626'041523   SC
00627'046101   AL
00630'020105   E
00631'040506   FA
00632'052103   CT
00633'051117   OR
00634'024040    (
00635'026116   N,
00636'051103   CR
00637'037451   )?
00640'000000   *
00641'027113   KMS:     .TXT     *K.
00642'027105   E.
00643'042520   PE
00644'045501   AK
00645'000000   *
```

```
00646'047504  03:       .TXT     *DO
00647'054440   Y
00650'052517  OU
00651'053440   W
00652'051511  IS
00653'020110  H
00654'047524  TO
00655'052440   U
00656'042523  SE
00657'040440   A
00660'052125  UT
00661'041517  OC
00662'050117  OP
00663'020131  Y
00664'051117  OR
00665'040440   A
00666'052125  UT
00667'051517  OS
00670'047524  TO
00671'020120  P
00672'054450  (Y
00673'047057  /N
00674'037451  )?
00675'000000  *
00676'044127  04:       .TXT     *WH
00677'052101  AT
00700'053440   W
00701'052517  OU
00702'042114  LD
00703'054440   Y
00704'052517  OU
00705'046040   L
00706'045511  IK
00707'020105  E
00710'051501  AS
00711'052040   T
00712'042510  HE
00713'041440   C
00714'050117  OP
00715'020131  Y
00716'047111  IN
00717'051103  CR
00720'046505  EM
00721'047105  EN
00722'020124  T
00723'047050  (N
00724'041454  ,C
00725'024522  R)
00726'000077  ?*
00727'052101  05:       .TXT     *AT
00730'053440   W
00731'040510  HA
00732'020124  T
00733'047520  PO
00734'047111  IN
00735'020124  T
00736'047527  WO
00737'046125  UL
00740'020104  D
00741'047531  YO
```

```
---
00742'020125  U
00743'044514  LI
00744'042513  KE
00745'052040   T
00746'020117  O
00747'052123  ST
00750'050117  OP
00751'024040   (
00752'026116  N,
00753'051103  CR
00754'037451  )?
00755'000000  *
00756'047516  N2:       .TXT     *NO
00757'042524  TE
00760'020072  :
00761'044124  TH
00762'020105  E
00763'047506  FO
00764'046114  LL
00765'053517  OW
00766'047111  IN
00767'020107  G
00770'052516  NU
00771'041115  MB
00772'051105  ER
00773'020123  S
00774'051101  AR
00775'020105  E
00776'052515  MU
00777'052114  LT
01000'050111  IP
01001'042514  LE
01002'020123  S
01003'043117  OF
01004'030440   1
01005'030060  00
01006'030060  00
01007'000000  *
01010'044450  N3:       .TXT     *(I
01011'026105  E,
01012'044124  TH
01013'020105  E
01014'047503  CO
01015'050115  MP
01016'020056  .
01017'047111  IN
01020'042524  TE
01021'050122  RP
01022'042522  RE
01023'051524  TS
01024'031040   2
01025'040440   A
01026'020123  S
01027'030062  20
01030'030060  00
01031'024460  0)
01032'000000  *
01033'044510  N4:       .TXT     *HI
01034'020124  T
01035'040503  CA
```

```
---
01036'051122  RR
01037'040511  IA
01040'042507  GE
01041'051040   R
01042'052105  ET
01043'051125  UR
01044'020116  N
01045'047524  TO
01046'042440   E
01047'044530  XI
01050'000124  T*
01051'047504  O6:       .TXT     *DO
01052'054440   Y
01053'052517  OU
01054'053440   W
01055'051511  IS
01056'020110  H
01057'047524  TO
01060'052440   U
01061'042523  SE
01062'045440   K
01063'042456  .E
01064'055056  .Z
01065'051105  ER
01066'024117  O(
01067'027531  Y/
01070'024516  N)
01071'000077  ?*
                        .END
```

```
                    .TITL   INPUT
                ;
                ;SEVERAL INPUT ROUTINES
                ;
                        .ENT    .SPRP,.INP,.UINP,.UD,.UW,.PSEG
                        .ENT    FEET,POUND,MOVFL,.PEMT,.PRES
                        .ENT    .LODE,.MOVE,.XCGD,.YCGD
                        .ENT    .SYCL,.MFLG,.DMBN,.DMBP
                        .EXTD   .PRNT,.FLIS,.PAGE,.MESS,.IPRN
                        .EXTD   MU,.DISS,.CURS,.ALPH,.PRN2
                        .EXTD   .AXIS,.DBIN,.GETT,.PRN2
                        .EXTD   .IPRN,.HITC
                        .EXTD   .CHEK,.WORD,.HITS,.DB0,.M7,.MEM
                        .EXTD   .MSKR,.LENG,.PONT,.PON2,.REBE
                        .EXTN   CONTR
                        .ZREL
00000-000277' .SPRP:    PROP
00001-000000' .INP:     INPUT
00002-001003' .LODE:    LODE
00003-001157' .SIGN:    SGN
00004-001174' .BRNG:    BRNG
00005-001202' .NGAT:    NGAT
00006-001043' .MOVE:    MOVE
00007-000000  .XCGD:    0       ;X DISP
00010-000000  .YCGD:    0       ;Y DISP
00011-000000  .SYCL:    0       ;DCM CYCLES
00012-000000  .MFLG:    0       ;DCM FLAG - 0=OFF
00013-000000  .DMBN:    0       ; " BLOCK NO.
00014-000000  .DMBP:    0       ; " BLOCK POINTER
00015-000000  .UD:      0       ;UNIT OF DISPLACEMENT
00016-000000  .UW:      0       ;UNIT WEIGHT
00017-000312' .UINP:    UINP    ;ENTRY FOR UNITS INPUT ROUTINE
00020-177777  .PEMT:    177777  ;PRESS. SEGMENT EMPTY HEAD
00021-177777  .PRES:    177777  ;PRESS. SEGMENT LIST HEAD
00022-000413' .PSEG:    EGGI
                        .NREL
      000012            .RDX    10
                ;
                ;DISPLAY PROPERTY TABLE AND WAIT FOR
                ;USER TO TYPE IN NEW FRICTION COEFFICIENTS.
                ;
00000'054467  INPUT:    STA     3,SPSAV
00001'006003S IN2:      JSR     @.PAGE
00002'006004S           JSR     @.MESS
00003'001222'           TEXT1
00004'177634            -100
00005'001130            600
00006'006004S           JSR     @.MESS
00007'001234'           TEXT2
00010'177634            -100
00011'001034            540
00012'006004S           JSR     @.MESS
00013'001237'           TEXT3
00014'177160            -400
00015'001034            540
00016'006004S           JSR     @.MESS
00017'001244'           TEXT4
00020'000144            100
00021'000776            510
00022'020006S           LDA     0,MU
```

```
---
00023'034456            JSR     FRAC
00024'000620            400
00025'000776            510
                  ;INITIALISE LOOP VARIABLES
00026'030000-           LDA     2,.SPRP
00027'151400            INC     2,2
00030'050440            STA     2,POINT
00031'020440            LDA     0,N16
00032'040434            STA     0,CNT
00033'014433            DSZ     CNT
00034'102520            SUBZL   0,0     ;START @ 1 NOT 0
00035'040435            STA     0,NUM
00036'020436            LDA     0,Y1
00037'040405            STA     0,YY
00040'040413            STA     0,YYY
                  ;SCAN THROUGH PROPERTY TYPES,
                  ;PRINTING FRICTION FOR EACH
00041'006004S TOP:      JSR     @.MESS
00042'001256'           TEXTS
00043'000144            100
00044'000000  YY:       0
00045'020425            LDA     0,NUM
00046'006005S           JSR     @.IPRN
00047'000002            2
00050'022420            LDA     0,@POINT        ;PROPERTY #
00051'004430            JSR     FRAC
00052'000620            400
00053'000000  YYY:      0
      000010            .RDX    8
00054'010414            ISZ     POINT
00055'010415            ISZ     NUM
00056'020415            LDA     0,YINC
00057'024774            LDA     1,YYY
00060'106400            SUB     0,1     ;NEW Y
00061'044772            STA     1,YYY
00062'044762            STA     1,YY
00063'014403            DSZ     CNT
00064'000755            JMP     TOP
00065'000446            JMP     GET
00066'000000  CNT:      0
00067'000000  SPSAV:    0
00070'000000  POINT:    0
00071'000012  N16:      12      ;SIZE OF PROPERTY TABLE
00072'000000  NUM:      0
      000012            .RDX    10
      000026  YROW=22
      000750  YTOP=488
      000414  YBOT=-10*YROW+YTOP
00073'000026  YINC:     YROW    ;DISTANCE BETWEEN LINES
00074'000722  Y1:       YTOP-YROW
00075'000764  X1:       500
00076'000414  YL:       YBOT
      000010            .RDX    8
00077'000215  CR:       15+200
00100'000256  DOT:      ".+200
              ;TO PRINT FRACTION (WITH N DECIMAL
              ;PLACES) AT (X,Y) ON SCREEN
              ;
              ;         JSR FRAC
              ;         X
```

```
                        ;          Y
                        ;FRACTION IN ACC
                        ;
          000003        N=3
00101'054424    FRAC:   STA     3,FSAV
00102'040424            STA     0,FR
00103'021400            LDA     0,0,3
00104'025401            LDA     1,1,3
00105'006002S           JSR     @.PLTS
00106'000000            0
00107'006001S           JSR     @.PRNI
00110'000037            37
00111'006001S           JSR     @.PRNI
00112'000060            "0
00113'006001S           JSR     @.PRNI
00114'000056            ".
00115'024411            LDA     1,FR
00116'030414            LDA     2,C1000
00117'102400            SUB     0,0
00120'073301            MUL
00121'006005S           JSR     @.IPRN
00122'177775            -N
00123'034402            LDA     3,FSAV
00124'001402            JMP     2,3
00125'000000    FSAV:   0
00126'000000    FR:     0
00127'000000    CHAR:   0
00130'000000    X:      0
00131'000000    Y:      0
          000012        .RDX    10
00132'001750    C1000:  1000    ;SET AT 10**N
          000010        .RDX    8
                        ;
                        ;PUT UP CURSOR AND WAIT
                        ;
00133'006010S   GET:    JSR     @.CURS
00134'000127'           CHAR
00135'000130'           X
00136'000131'           Y
00137'006011S           JSR     @.ALPH
00140'020767            LDA     0,CHAR
00141'024736            LDA     1,CR
00142'106414            SUB#    0,1,SZR ;CHECK FOR "RETURN"
00143'000405            JMP     NEXT
00144'006003S           JSR     @.PAGE  ;NO CHANGE; RETURN.
00145'006016S           JSR     @.TPRN
00146'006007S           JSR     @.DISS  ;AND EXIT
00147'002720            JMP     @SPSAV
00150'024730    NEXT:   LDA     1,DOT
00151'106414            SUB#    0,1,SZR ;CHECK FOR DEC. POINT
00152'000761            JMP     GET     ;NO GOOD; KEEP WAITING
00153'024756            LDA     1,Y
00154'020722            LDA     0,YL
00155'106423            SUBZ    0,1,SNC ;CHECK FOR LOWER LIMIT
00156'000755            JMP     GET
00157'102400            SUB     0,0
00160'030713            LDA     2,YINC
00161'073101            DIV
00162'020707            LDA     0,N16
00163'122423            SUBZ    1,0,SNC ;CHECK FOR UPPER LIMIT
```

```
00164'000424          JMP     TRYMU
00165'030000-         LDA     2,.SPRP
00166'113000          ADD     0,2      ;POINTER TO PROP TABLE
00167'050437          STA     2,PPNT
            ;SET UP LOCATION TO PRINT NEW NUMBER
00170'102400          SUB     0,0
00171'030702          LDA     2,YINC
00172'073301          MUL
00173'020703          LDA     0,YL
00174'107000          ADD     0,1
00175'020700          LDA     0,X1
00176'006002$         JSR     @.PLTS
00177'000000          0
00200'006011$         JSR     @.ALPH
00201'020726          LDA     0,CHAR
00202'006012$         JSR     @.PRN2
00203'004430          JSR     KEYB
00204'020425          LDA     0,SUM
00205'030421          LDA     2,PPNT
00206'041000          STA     0,0,2    ;STORE NEW FRICTION
00207'000724          JMP     GET
00210'101404  TRYMU:  INC     0,0,SZR  ;CHECK FOR DEFAULT VALUE
00211'000722          JMP     GET
00212'024413          LDA     1,YMU
00213'020662          LDA     0,X1
00214'006002$         JSR     @.PLTS
00215'000000          0
00216'006011$         JSR     @.ALPH
00217'020710          LDA     0,CHAR   ;SEND OUT DEC. POINT
00220'006012$         JSR     @.PRN2
00221'004412          JSR     KEYB
00222'020407          LDA     0,SUM
00223'040006$         STA     0,MU
00224'000707          JMP     GET
00225'000776  YMU:    13*YROW+YBOT
00226'000000  PPNT:   0
00227'000000  NN:     0
00230'000005  NTIM:   5
00231'000000  SUM:    0
00232'000000  KSAV:   0
00233'054777  KEYB:   STA     3,KSAV
00234'034434          LDA     3,TBL
00235'054432          STA     3,TBLSV
00236'102400          SUB     0,0
00237'040772          STA     0,SUM
00240'020770          LDA     0,NTIM
00241'040766          STA     0,NN
00242'006015$ GIT:    JSR     @.GETT
00243'006012$         JSR     @.PRN2
00244'006020$         JSR     @.CHEK
00245'000415          JMP     ERROR
00246'105000          MOV     0,1
00247'034420          LDA     3,TBLSV
00250'021400          LDA     2,0,3    ;GET MULTIPLIER
00251'102400          SUB     0,0
00252'073301          MUL
00253'020756          LDA     0,SUM
00254'123000          ADD     1,0      ;ADD IN NEW DIGIT
00255'040754          STA     0,SUM
00256'010411          ISZ     TBLSV
```

```
---
00257'014750          DSE     NN
00260'000762          JMP     GIT
00261'002751          JMP     @KSAV    ;EXIT FOR TOO MANY DIGITS
00262'024414  ERROR:  LDA     1,CRNP
00263'122415          SUB#    1,0,SNR
00264'002746          JMP     @KSAV    ;GOOD EXIT
00265'002401          JMP     @INP     ;BAD EXIT
00266'000001' INP:    IN2
00267'000000  TBLSV:  0
      014631  A1=77777/5
      000012          .RDX    10
      001217  A2=A1/10
      000101  A3=A2/10
      000006  A4=A3/10
      000000  A5=A4/10
      000010          .RDX    8
00270'000271' TBL:    .+1
00271'014631          A1
00272'001217          A2
00273'000101          A3
00274'000006          A4
00275'000000          A5
00276'000015  CRNP:   15      ;CARRIAGE RET. NO PAR.
      000000  PROP:
              ;TABLE FOR FRICTION COEFFICIENTS
      000012          .BLK    12
              ;
              ;
              ;ROUTINE TO ACCEPT INPUT OF UNITS FROM SCREEN
              ;
      000012          .RDX    10
00311'000000  USAV:   0
00312'054777  UINP:   STA     3,USAV
00313'006003S         JSR     @.PAGE
00314'006004S         JSR     @.MESS
00315'001264'         TEXT8
00316'177634          -100
00317'001130          600
00320'006004S         JSR     @.MESS
00321'001305'         TEXT9
00322'177634          -100
00323'001065          565
00324'006004S         JSR     @.MESS
00325'001312'         TEX10
00326'000342          226
00327'001065          565
00330'006013S         JSR     @.AXIS
00331'001412          778
00332'000144          100
00333'000550          360
00334'006004S         JSR     @.MESS
00335'001337'         TEX11
00336'000144          100
00337'000620          400
00340'006014S         JSR     @.DBIN   ;GET DISTANCE UNIT
00341'044015-         STA     1,.UD
00342'006021S         JSR     @.WORD   ;GET STRING
00343'000361'         FEET             ;STORAGE LOCATION
00344'006004S         JSR     @.MESS
00345'001365'         TEX12
---
```

```
00346'000144            100
00347'000310            200
      000010            .RDX     8
00350'006014S           JSR      @.DBIN  ;GET UNIT WEIGHT
00351'044016-           STA      1,.UW
00352'006021S           JSR      @.WORD  ;FORCE DESCRIPTOR
00353'000372'           POUND
00354'006015S           JSR      @.GETT
00355'006003S           JSR      @.PAGE
00356'006016S           JSR      @.TPRN
00357'006007S           JSR      @.DISS
00360'002731            JMP      @USAV
      000011 FEET:      .BLK     11      ;BYTE STRING FOR DISPL.
      000011 POUND:     .BLK     11      ;BYTE STRING FOR FORCE
             ;
             ;INPUT OF PRESSURE SEGMENTS
             ;
00403'006004S ERR:      JSR      @.MESS
      000012            .RDX     10
00404'001417'           TOBIG
00405'000310            200
00406'000764            500
      000010            .RDX     8
00407'000405            JMP      EGGS
00410'000000 EGG3:      0
00411'000000 FORIN:     0
      000012            .RDX     10
00412'000175 N125:      125
      000010            .RDX     8
00413'054775 EGG1:      STA      3,EGG3
00414'006010S EGGS:     JSR      @.CURS
00415'000604'           CHAR1
00416'000605'           XP
00417'000606'           YP
00420'020564            LDA      0,CHAR1
00421'006020S           JSR      @.CHEK
00422'002766            JMP      @EGG3   ;EXIT
00423'006011S           JSR      @.ALPH
00424'006022S           JSR      @.HITS
00425'000605'           XP
00426'000606'           YP
00427'000765            JMP      EGGS    ;NO HIT
00430'050557            STA      2,AC2B  ;BLOCK POINTER
00431'044557            STA      1,NP    ;EDGE #
00432'040557            STA      0,NB    ;BLOCK #
00433'054557            STA      3,ZIMM  ;RE-ENTRY ADDRESS
00434'020551            LDA      0,XP
00435'024551            LDA      1,YP
00436'030555            LDA      2,CS    ;OFFSET
00437'142400            SUB      2,0
00440'146400            SUB      2,1
00441'006002S           JSR      @.PLTS
00442'000000            0
00443'006011S           JSR      @.ALPH
00444'006001S           JSR      @.PRN1  ;PRINT * ON SELECTED
00445'000052            "*               ;EDGE
00446'020536            LDA      0,CHAR1 ;GET INITIAL CHARACTER BACK
00447'006023S           JSR      @.DB0   ;NOW GET THE REST
00450'030572            LDA      2,CRR
00451'142414            SUB#     2,0,SZR ;CHECK FOR CR
```

```
00452'002736            JMP     @EGG3    ;EXIT
00453'044736            STA     1,FORIN
00454'030533            LDA     2,AC2B
00455'024533            LDA     1,NP
00456'006027S           JSR     @.LENG
00457'105000            MOV     2,1
00460'030731            LDA     2,FORIN
00461'102400            SUB     0,0
00462'073301            MUL
00463'030727            LDA     2,N125
00464'142513            SUBL#   2,0,SNC ;CHECK BEFORE DIVIDING
00465'000716            JMP     ERR
00466'073101            DIV
00467'044554            STA     1,FORCE
00470'000572            JMP     COMPM    ;COMPUTE MOMENT
00471'004440   TWIT:    JSR     EXIST    ;SEE IF SEGMENT EXISTS
00472'000463            JMP     NEWEN    ;NO, MAKE A NEW ONE
00473'020550            LDA     0,FORCE
00474'101004            MOV     0,0,SZR ;CHECK FOR ZERO FORCE
00475'000524            JMP     RESTI    ;ENTER NEW FORCE IN OLD SEG.
               ;THE FOLLOWING DELETES A DEAD PRESSURE SEGMENT
00476'021002            LDA     0,2,2    ;LINK FIELD IN DEAD SEG.
00477'041400            STA     0,0,3    ;STORE IN PREVIOUS ONE
00500'020020-           LDA     0,.PEMT ;EMPTY LIST HEAD
00501'050020-           STA     2,.PEMT ;ADDR. OF DEAD SEG.
00502'041002            STA     0,2,2    ;LINK UP WITH OTHERS
               ;NOW SEE IF THERE ARE ANY MORE HITS
00503'034507   AGAIN:   LDA     3,ZIMM
00504'005401            JSR     1,3      ;RE-ENTER "HITS" WITH
00505'000605'           XP               ;RETURN TO HERE
00506'000606'           YP
00507'000705            JMP     EGGS     ;NO MORE HITS
00510'054502            STA     3,ZIMM
00511'050476            STA     2,AC2B
00512'044476            STA     1,NP
00513'040476            STA     0,NB
00514'006027S           JSR     @.LENG
00515'105000            MOV     0,1
00516'030673            LDA     2,FORIN
00517'102400            SUB     0,0
00520'073301            MUL
00521'030671            LDA     2,N125
00522'142513            SUBL#   2,0,SNC ;CHECK BEFORE DIVIDING
00523'000660            JMP     ERR
00524'073101            DIV
00525'044516            STA     1,FORCE
00526'000534            JMP     COMPM    ;AROUND WE GO AGAIN
               ;THE FOLLOWING CHECKS IF A PRESSURE SEG. ALREADY EXISTS
00527'000000   EX3:     0
00530'000021-  PRADD:   .PRES
00531'030021-  EXIST:   LDA     2,.PRES ;LIST HEAD
00532'151112            MOVL#   2,2,SEC
00533'001400            JMP     0,3      ;NO SEGMENTS
00534'054773            STA     3,EX3
00535'024454            LDA     1,NB
00536'020452            LDA     0,NP
00537'101300            MOVS    0,0
00540'107000            ADD     0,1      ;NPNB
00541'034767            LDA     3,PRADD ;PREVIOUS HEAD IN AC3
00542'021000   ANCHOR:  LDA     0,0,2    ;1ST WORD
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00543'106414            SUB#    0,1,SZR ;SAME NPNB?
00544'000403            JMP     CHAIN   ;NO; KEEP GOING
00545'010762            ISZ     EX3
00546'002761            JMP     @EX3    ;GOOD EXIT
00547'155400    CHAIN:  INC     2,3
00550'175400            INC     3,3
00551'031002            LDA     2,2,2   ;NEW SEG.
00552'151112            MOVL#   2,2,SZC
00553'002754            JMP     @EX3    ;END OF CHAIN; EXIT!
00554'000766            JMP     ANCHOR
                ;THE FOLLOWING CREATES A NEW PRESSURE SEG. ENTRY
00555'020466    NEWEN:  LDA     0,FORCE
00556'101005            MOV     0,0,SNR
00557'000724            JMP     AGAIN
00560'030020-           LDA     2,.PEMT ;TRY EMPTY P. LIST
00561'151112            MOVL#   2,2,SZC
00562'000407            JMP     FRMEM   ;MUST USE VIRGIN MEMORY
00563'021002            LDA     0,2,2   ;OLD LINK
00564'040020-           STA     0,.PEMT ;REVISE EMPT POINTER
00565'034021-           LDA     3,.PRES ;CURRENT HEAD OF P. LIST
00566'055002            STA     3,2,2   ;NEW LINK
00567'050021-           STA     2,.PRES ;INSERT NEW P. SEG.
00570'000430            JMP     REST    ;NOW PUT IN DATA
00571'030024S   FRMEM:  LDA     2,.M7   ;NEXT FREE LOCATION.
00572'020025S           LDA     0,.MEM  ;HIGHEST MEMORY
00573'024452            LDA     1,SIZPR ;WORDS NEEDED
00574'147000            ADD     2,1
00575'122513            SUBL#   1,0,SNC ;OVERFLOW?
00576'000416            JMP     ALLOK   ;NO
      000012            .RDX    10
00577'006004S           JSR     @.MESS  ;PUT OUT MESSAGE
00600'001406'           MOVFL
00601'000310            200
00602'000574            380
      000010            .RDX    8
00603'000700            JMP     AGAIN
00604'000000    CHAR1:  0
00605'000000    XP:     0
00606'000000    YP:     0
00607'000000    AC2B:   0
00610'000000    NP:     0
00611'000000    NB:     0
00612'000000    ZIMM:   0
00613'000000    CS:     0
00614'044024S   ALLOK:  STA     1,.M7   ;REVISE FREE POINTER
00615'020021-           LDA     0,.PRES
00616'041002            STA     0,2,2
00617'050021-           STA     2,.PRES
00620'020423    REST:   LDA     0,FORCE ;NORMAL FORCE
00621'041001    REST1:  STA     0,1,2
00622'020422            LDA     0,MOMNT ;MOMENT
00623'041003            STA     0,3,2
00624'024765            LDA     1,NB
00625'020763            LDA     0,NP
00626'101300            MOVS    0,0
00627'123000            ADD     1,0     ;NPNB
00630'041000            STA     0,0,2   ;HEAD OF GROUP
00631'030756            LDA     2,AC2B  ;BLOCK POINTER
00632'021000            LDA     0,0,2   ;CONTROL WORD
00633'100000            COM     0,0
```

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---
00634'034412          LDA     3,PFLAG
00635'163400          AND     3,0
00636'100000          COM     0,0
00637'041000          STA     0,0,2   ;SET PRESSURE FLAG
00640'006032$         JSR     @.REBE  ;REBOX; UPDATE FX,FY
00641'000642          JMP     AGAIN
00642'000015  CRR:    15
00643'000000  FORCE:  0
00644'000000  MOMNT:  0
00645'000006  SIZPR:  6
00646'177377  PFLAG:  177377
00647'000000  XA:     0
00650'000000  XB:     0
00651'000000  YA:     0
00652'000000  YB:     0
00653'000000  LNG:    0
00654'000000  XD:     0
00655'000000  YD:     0
00656'000000  XCC:    0
00657'000000  YCC:    0
00660'000000  HI:     0
00661'000000  LO:     0
              ;
00662'030725  COMPM:  LDA     2,AC2B
00663'024725          LDA     1,NP
00664'006030$         JSR     @.PON1
00665'040762          STA     0,XA
00666'044763          STA     1,YA
00667'024721          LDA     1,NP
00670'006027$         JSR     @.LENG
00671'040762          STA     0,LNG
00672'021000          LDA     0,0,2
00673'034026$         LDA     3,.MSKR
00674'163400          AND     3,0
00675'125400          INC     1,1
00676'122415          SUB#    1,0,SNR
00677'126400          SUB     1,1     ;MUST BE FIRST CORNER
00700'006031$         JSR     @.PON2
00701'034746          LDA     3,XA
00702'162400          SUB     3,0     ;XB-XA
00703'034746          LDA     3,YA
00704'166400          SUB     3,1     ;YB-YA
00705'040747          STA     0,XD
00706'044747          STA     1,YD
00707'021001          LDA     0,1,2   ;XC
00710'024675          LDA     1,XP    ;MID-POINT
00711'122400          SUB     1,0
00712'040744          STA     0,XCC
00713'021003          LDA     0,3,2   ;YC
00714'024672          LDA     1,YP
00715'122400          SUB     1,0
00716'040741          STA     0,YCC
00717'004446          JSR     SMUL    ;SIGNED MULTIPLY
00720'000655'         YD
00721'000657'         YCC
00722'040736          STA     0,HI
00723'044736          STA     1,LO
00724'004441          JSR     SMUL
00725'000654'         XD
00726'000656'         XCC
```

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---
00727'030731            LDA     2,HI
00730'034731            LDA     3,LO
00731'167022            ADDZ    3,1,SZC ;ADD 2 DP NUMBERS
00732'151400            INC     2,2
00733'143000            ADD     2,0
00734'176400            SUB     3,3
00735'101113            MOVL#   0,0,SNC ;NEGATIVE?
00736'000405            JMP     NONEG   ;NO
00737'124405            NEG     1,1,SNR
00740'100401            NEG     0,0,SKP
00741'100000            COM     0,0
00742'176520            SUBZL   3,3
00743'030710 NONEG:     LDA     2,LNG
00744'073101            DIV
00745'030676            LDA     2,FORCE
00746'102400            SUB     0,0
00747'073301            MUL
00750'175005            MOV     3,3,SNR
00751'000404            JMP     BIT8
00752'124405            NEG     1,1,SNR
00753'100401            NEG     0,0,SKP
00754'100000            COM     0,0
00755'030026S BIT8:     LDA     2,.MSKR ;TAKE MIDDLE 8 BITS
00756'143700            ANDS    2,0
00757'125300            MOVS    1,1
00760'147400            AND     2,1
00761'107000            ADD     0,1     ;RESULT IN AC1
00762'044662            STA     1,MOMNT
00763'002417            JMP     @TWT
00764'000000 SMUL3:     0
00765'054777 SMUL:      STA     3,SMUL3
00766'027400            LDA     1,@0,3
00767'033401            LDA     2,@1,3
00770'176400            SUB     3,3
00771'125112            MOVL#   1,1,SZC
00772'157000            ADD     2,3
00773'151112            MOVL#   2,2,SZC
00774'137000            ADD     1,3
00775'102400            SUB     0,0
00776'073301            MUL
00777'162400            SUB     3,0
01000'034764            LDA     3,SMUL3
01001'001402            JMP     2,3
01002'000471' TWT:      TWIT
                     ;
                     ; APPLIED LOAD INPUT ( NUM. )
                     ;
01003'050437 LODE:      STA     2,BLKPT
01004'006004S           JSR     @.MESS
01005'001431'           NEWX
01006'000175            125.
01007'000113            75.
01010'006003- XLOD:     JSR     @.SIGN  ;GET SIGN OF LOAD
01011'006004-           JSR     @.BRNG  ;GET LOAD
01012'006004S           JSR     @.MESS
01013'001445'           SMES
01014'000416            270.
01015'000113            75.
01016'000772            JMP     XLOD
01017'006005-           JSR     @.NGAT
---
```

```
01020'030422          LDA     2,BLKPT
01021'045023          STA     1,23,2  ;PUT IT IN LIST
                ;
01022'006004S         JSR     @.MESS
01023'001437'         NEWY
01024'000175          125.
01025'000067          55.
01026'006003- YLOD:   JSR     @.SIGN
01027'006004-         JSR     @.BRNG
01030'006004S         JSR     @.MESS
01031'001445'         SMES
01032'000416          270.
01033'000067          55.
01034'000772          JMP     YLOD
01035'006005-         JSR     @.NGAT
01036'030404          LDA     2,BLKPT
01037'045024          STA     1,24,2
01040'002401          JMP     @CONT
01041'177777  CONT:   CONTR
                ;
01042'000000  BLKPT:  0
                ;
                ;
                ; DISPLACEMENT CONTROL ROUTINE
                ;
01043'006004S MOVE:   JSR     @.MESS
01044'001577'         BMES
01045'000144          100.
01046'000144          100.
01047'006010S         JSR     @.CURS  ;SELECT BLOCK
01050'001154'         CHRC
01051'001155'         XDM
01052'001156'         YDM
01053'006017S         JSR     @.HITC
01054'001155'         XDM
01055'001156'         YDM
01056'000765          JMP     MOVE    ;TRY AGAIN
01057'020475          LDA     0,CHRC  ; IS IT AN "E"
01060'034473          LDA     3,ESKP  ;IF SO EXIT AND
01061'116415          SUB#    0,3,SNR ; UNHOOK DCM
01062'000531          JMP     FNSH
01063'050014-         STA     2,.DMBP ;BLOCK POINTER
01064'044013-         STA     1,.DMBN ;AND NUMBER
01065'176520          SUBZL   3,3     ;GEN A 1
01066'054012-         STA     3,.MFLG ; ALERT DCM
                ;
                ;---- ACCEPT DISPLACEMENTS
                ;
01067'006003S         JSR     @.PAGE
01070'006004S         JSR     @.MESS
01071'001457'         DMS1
01072'177470          -200.
01073'000764          500.
01074'006004S         JSR     @.MESS
01075'001477'         DMS2
01076'000341          225.
01077'000733          475.
01100'006004S         JSR     @.MESS
01101'001515'         DMS3
01102'000226          150.
```

```
01103'000620          400.
01104'006003- CGX:    JSR      @.SIGN
01105'006004-         JSR      @.BRNG
01106'006004$         JSR      @.MESS
01107'001445'         SMES
01110'000764          500.
01111'000620          400.
01112'000772          JMP      CGX
01113'006005-         JSR      @.NGAT
01114'044007-         STA      1,.XCGD
              ;
01115'006004$         JSR      @.MESS
01116'001531'         DMS4
01117'000226          150.
01120'000536          350.
01121'006003- CGY:    JSR      @.SIGN
01122'006004-         JSR      @.BRNG
01123'006004$         JSR      @.MESS
01124'001445'         SMES
01125'000764          500.
01126'000536          350.
01127'000772          JMP      CGY
01130'006005-         JSR      @.NGAT
01131'044010-         STA      1,.YCGD
              ;
01132'006004$         JSR      @.MESS
01133'001614'         DMS7
01134'000226          150.
01135'000454          300.
01136'020451          LDA      0,PLUS
01137'006004-         JSR      @.BRNG
      000005          .BLK     5         ;NEED 5 SPACES TO USE .BRNG
01145'044011-         STA      1,.SYCL
              ;
01146'006004$         JSR      @.MESS
01147'001545'         DMS5
01150'000310          200.
01151'000372          250.
01152'002667          JMP      @ CONT
              ;
01153'000305  ESKP:   "E+200             ;ADD PARITY BIT
01154'000000  CHRC:   0
01155'000000  XDM:    0
01156'000000  YDM:    0
              ;
              ;-----------
              ;
01157'054432  SGN:    STA      3,GOBK
01160'006015$         JSR      @.GETT   ; + OR - FIRST
01161'040431          STA      0,SIGN
01162'024425          LDA      1,PLUS
01163'106415          SUB#     0,1,SNR ; MUST BE +
01164'000406          JMP      OK1      ; OUT IF +
01165'024423          LDA      1,MNUS
01166'106415          SUB#     0,1,SNR ;MUST BE -
01167'000403          JMP      OK1      ; OUT IF -
01170'034421          LDA      3,GOBK
01171'001401          JMP      1,3
01172'034417  OK1:    LDA      3,GOBK
01173'001400          JMP      0,3
```

```
                  ;
                  ;-------------
                  ;
01174'054415  BRNG:    STA    3,GOBK
01175'020415           LDA    0,SIGN
01176'006012S          JSR    @.PRN2  ;PRINT SIGN
01177'006014S          JSR    @.DBIN  ; X LOAD IS IN AC1
01200'034411           LDA    3,GOBK
01201'001405           JMP    5,3
                  ;
                  ;-------------
                  ;
01202'020410  NGAT:    LDA    0,SIGN  ;SIGN OF NEW LOAD
01203'030405           LDA    2,MNUS  ;ASCII -
01204'112415           SUB#   0,2,SNR
01205'124400           NEG    1,1
01206'001400           JMP    0,3
                  ;
01207'000053  PLUS:    "+
01210'000055  MNUS:    "-
01211'000000  GOBK:    0
01212'000000  SIGN:    0
                  ;
01213'126400  FNSH:    SUB    1,1
01214'044012-          STA    1,.MFLG ;TURN OFF FLAG
01215'006004S          JSR    @.MESS
01216'001562'          DMS6
01217'177324           -300.
01220'001130           600.
01221'002620           JMP    @CONT
                  ;
01222'052523  TEXT1:   .TXT   *SU
01223'043122  RF
01224'041501  AC
01225'020105  E
01226'051120  PR
01227'050117  OP
01230'051105  ER
01231'044524  TI
01232'051505  ES
01233'000000  *
01234'054524  TEXT2:   .TXT   *TY
01235'042520  PE
01236'000000  *
01237'051106  TEXT3:   .TXT   *FR
01240'041511  IC
01241'044524  TI
01242'047117  ON
01243'000000  *
01244'042504  TEXT4:   .TXT   *DE
01245'040506  FA
01246'046125  UL
01247'020124  T
01250'052050  (T
01251'050131  YP
01252'020105  E
01253'020043  #
01254'024460  0)
01255'000000  *
01256'051120  TEXT5:   .TXT   *PR
```

```
---
01257'052117  OP
01260'051105  ER
01261'054524  TY
01262'021440   #
01263'000040   *
01264'047111  TEXT8:  .TXT     *IN
01265'052520  PU
01266'020124  T
01267'043117  OF
01270'042040   D
01271'051511  IS
01272'040524  TA
01273'041516  NC
01274'020105  E
01275'047101  AN
01276'020104  D
01277'047506  FO
01300'041522  RC
01301'020105  E
01302'047125  UN
01303'052111  IT
01304'000123  S*
01305'040503  TEXT9:  .TXT     *CA
01306'052125  UT
01307'047511  IO
01310'035116  N:
01311'000000  *
01312'047117  TEX10:  .TXT     *ON
01313'054514  LY
01314'047040   N
01315'046525  UM
01316'042502  BE
01317'051522  RS
01320'043040   F
01321'047522  RO
01322'020115  M
01323'020061  1
01324'044124  TH
01325'047522  RO
01326'043525  UG
01327'020110  H
01330'030065  50
01331'030060  00
01332'040440   A
01333'046114  LL
01334'053517  OW
01335'042105  ED
01336'000000  *
01337'044127  TEX11:  .TXT     *WH
01340'052101  AT
01341'042040   D
01342'020117  O
01343'047531  YO
01344'020125  U
01345'040527  WA
01346'052116  NT
01347'052040   T
01350'044510  HI
01351'020123  S
01352'042514  LE
---
```

```
01353'043516  NG
01354'044124  TH
01355'052040   T
01356'020117  O
01357'042522  RE
01360'051120  PR
01361'051505  ES
01362'047105  EN
01363'037524  T?
01364'000040   *
01365'044127  TEX12:  .TXT    *WH
01366'052101  AT
01367'044440   I
01370'020123  S
01371'044124  TH
01372'020105  E
01373'047125  UN
01374'052111  IT
01375'053440   W
01376'044505  EI
01377'044107  GH
01400'020124  T
01401'043117  OF
01402'051040   R
01403'041517  OC
01404'037513  K?
01405'000040   *
01406'046407  MOVFL:  .TXT    *<7>M
01407'046505  EM
01410'051117  OR
01411'020131  Y
01412'053117  OV
01413'051105  ER
01414'046106  FL
01415'053517  OW
01416'000000  *
01417'050007  TOBIG:  .TXT    *<7>P
01420'042522  RE
01421'051523  SS
01422'051125  UR
01423'020105  E
01424'047524  TO
01425'020117  O
01426'040514  LA
01427'043522  RG
01430'000105  E*
01431'042516  NEWX:   .TXT    *NE
01432'020127  W
01433'020130  X
01434'047514  LO
01435'042101  AD
01436'000040   *
01437'042516  NEWY:   .TXT    *NE
01440'020127  W
01441'020131  Y
01442'047514  LO
01443'042101  AD
01444'000040   *
01445'051440  SMES:   .TXT    * S
01446'043511  IG
```

```
---
01447'020116  N
01450'044506  FI
01451'051522  RS
01452'020124  T
01453'046120  PL
01454'040505  EA
01455'042523  SE
01456'000040   *
01457'047111  DMS1:    .TXT     *IN
01460'052520  PU
01461'020124  T
01462'044506  FI
01463'042530  XE
01464'020104  D
01465'046102  BL
01466'041517  OC
01467'020113  K
01470'044504  DI
01471'050123  SP
01472'040514  LA
01473'042503  CE
01474'042515  ME
01475'052116  NT
01476'000123  S*
01477'031050  DMS2:    .TXT     *(2
01500'054105  EX
01501'030520  P1
01502'020066  6
01503'051511  IS
01504'047440   O
01505'042516  NE
01506'051440   S
01507'051103  CR
01510'042505  EE
01511'020116  N
01512'047125  UN
01513'052111  IT
01514'000051  )*
01515'020130  DMS3:    .TXT     *X
01516'042503  CE
01517'052116  NT
01520'047522  RO
01521'042111  ID
01522'042040   D
01523'051511  IS
01524'046120  PL
01525'041501  AC
01526'046505  EM
01527'047105  EN
01530'000124  T*
01531'020131  DMS4:    .TXT     *Y
01532'042503  CE
01533'052116  NT
01534'047522  RO
01535'042111  ID
01536'042040   D
01537'051511  IS
01540'046120  PL
01541'041501  AC
01542'046505  EM
---
```

```
01543'047105  EN
01544'000124  T*
01545'044506  DMS5:   .TXT    *FI
01546'044516  NI
01547'044123  SH
01550'042105  ED
01551'053454  ,W
01552'044501  AI
01553'044524  TI
01554'043516  NG
01555'040440   A
01556'020124  T
01557'047503  CO
01560'052116  NT
01561'000122  R*
01562'047125  DMS6:   .TXT    *UN
01563'047510  HO
01564'045517  OK
01565'042105  ED
01566'042040   D
01567'046503  CM
01570'026440   -
01571'020055  -
01572'052101  AT
01573'041440   C
01574'047117  ON
01575'051124  TR
01576'000000  *
01577'042523  BMES:   .TXT    *SE
01600'042514  LE
01601'052103  CT
01602'041040   B
01603'047514  LO
01604'045503  CK
01605'044054  ,H
01606'052111  IT
01607'040440   A
01610'054516  NY
01611'045440   K
01612'054505  EY
01613'000000  *
01614'041440  DMS7:   .TXT    * C
01615'041531  YC
01616'042514  LE
01617'020123  S
01620'042502  BE
01621'053524  TW
01622'042505  EE
01623'020116  N
01624'047515  MO
01625'042526  VE
01626'020123  S
01627'000000  *
                      .END
```

```
                        .TITL   MOVIT
                  ;
                  ;ROUTINE TO EXTERNALLY MOVE A FIXED BLOCK
                  ;
                        .ENT    .DCM
                        .EXTD   .DISB,.MESS,.REBX,.PFLG
                        .EXTD   .MOT,.FORD,.ALLB,.XCGD,.YCGD
                        .EXTD   .SYCL,.MFLG,.STEP,.DMBN,.DMBP
                        .ZREL
00000-000002' .DCM:     MOVE
                        .NREL
                  ;
00000'000000  RET3:     0
00001'000001  DMCT:     1
                  ;
00002'054776  MOVE:     STA     3,RET3
00003'024013$           LDA     1,.MFLG ;CHECK IF DCM
00004'125005            MOV     1,1,SNR
00005'002773            JMP     @ RET3  ;GO BACK NO DCM
00006'014773            DSZ     DMCT    ;ONLY EVERY .SYCL CY
00007'002771            JMP     @ RET3  ;GO BACK NOT RIGHT
00010'034012$           LDA     3,.SYCL
00011'054770            STA     3,DMCT  ;RESET COUNTER
00012'024010$           LDA     1,.XCGD ;APPLIED X DISP
00013'135000            MOV     1,3
00014'125112            MOVL#   1,1,SZC ;CHECK FOR SIGN
00015'124400            NEG     1,1
00016'030016$ DCMX:     LDA     2,.DMBP
00017'021002            LDA     0,2,2   ;XC(LOW)
00020'175112            MOVL#   3,3,SZC
00021'000405            JMP     FLIT    ;WAS NEGATIVE
00022'123023            ADDZ    1,0,SNC
00023'000417            JMP     OK
00024'011001            ISZ     1,2     ;INCREMENT XC(HIGH)
00025'000405            JMP     CHECK
00026'124400  FLIT:     NEG     1,1
00027'123022            ADDZ    1,0,SZC
00030'000412            JMP     OK
00031'015001            DSZ     1,2     ;DECREMENT XC(HIGH)
00032'045020  CHECK:    STA     1,20,2  ;DEL XC
00033'041002            STA     0,2,2
00034'024015$           LDA     1,.DMBN
00035'006003$           JSR     @.REBX  ;RE-CLASSIFY THIS BLOCK
00036'034004$           LDA     3,.PFLG
00037'175005            MOV     3,3,SNR
00040'006001$           JSR     @.DISB
00041'000403            JMP     NUT
00042'045020  OK:       STA     1,20,2  ;DEL XC
00043'041002            STA     0,2,2   ;NEW XC(LOW)
                  ;
00044'024011$ NUT:      LDA     1,.YCGD ;APPLIED Y DISP
00045'135000            MOV     1,3
00046'125112            MOVL#   1,1,SZC ;AS ABOVE
00047'124400            NEG     1,1
00050'030016$ DCMY:     LDA     2,.DMBP
00051'021004            LDA     0,4,2   ;YC(LOW)
00052'175112            MOVL#   3,3,SZC
00053'000405            JMP     FLITS
00054'123023            ADDZ    1,0,SNC
00055'000417            JMP     OKS
```

```
00056'011003           ISZ     3,2        ;INCREMENT YC(HIGH)
00057'000405           JMP     CHECS
00060'124400  FLITS:   NEG     1,1
00061'123022           ADDZ    1,0,SZC
00062'000412           JMP     OKS
00063'015003           DSZ     3,2        ;DECREMENT YC(HIGH)
00064'045021  CHECS:   STA     1,21,2     ;DELYC
00065'041004           STA     0,4,2
00066'024015$          LDA     1,.DMBN
00067'006003$          JSR     @.REBX     ;RE-CLASSIFY
00070'034004$          LDA     3,.PFLG
00071'175005           MOV     3,3,SNR
00072'006001$          JSR     @.DISB     ;PLOT JUST THIS BLOCK
00073'000403           JMP     CLIT
00074'045021  OKS:     STA     1,21,2     ;DELYC
00075'041004           STA     0,4,2      ;NEW YC(LOW)
              ;
00076'060477  CLIT:    READS   0          ;CHECK FOR SW 0
00077'101122           MOVZL   0,0,SZC    ;OFF = MESS
00100'000405           JMP DUDE
00101'006002$          JSR     @.MESS
00102'000117'          MOMS
00103'000144           100.
00104'000144           100.
00105'006005$ DUDE:    JSR     @.MOT
00106'006006$          JSR     @.FORD
00107'006014$          JSR     @.STEP
00110'030016$          LDA     2,.DMBP    ;GET BLOCK POINTER
00111'102400           SUB     0,0        ;SET ALL TO 0
00112'041020           STA     0,20,2     ;DEL X
00113'041021           STA     0,21,2     ;DEL Y
00114'041022           STA     0,22,2     ;DEL AL
00115'006007$          JSR     @.ALLB     ;UPDATE CONTACTS
00116'002662           JMP     @RET3      ;GO BACK
              ;
00117'047515  MOMS:    .TXT    *MO
00120'042526  VE
00121'020104  D
00122'000041  !*
              ;
                       .END
```

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  Rational design of tunnel supports: an interactive graphics based analysis of the support requirements of excavations in jointed rock masses / by Michael D. Voegele, Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, Minn. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
  v, [516] p. ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; GL-79-15)
  Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW45-74-C-0066.
  References: p. R-1 - R-9.

1. Excavation. 2. Interactive graphics. 3. Jointed rock. 4. Rock masses. 4. Tunnel supports. I. Minnesota. University. Dept. of Civil and Mineral Engineering. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; GL-79-15.
TA7.W34 no.GL-79-15